A SYSTEMS ANALYSIS OF FIRE SUPPRESSION ALTERNATIVES FOR THE U.S. SPACE STATION

THESIS

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Greg Sheridan

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Abstract

NASA's 'front line' defense against fire aboard manned spacecraft has been strict control of materials, construction, and operation. This will continue with the space station, but the inclusion of laboratory facilities and crew comfort features combined with the increasing 'routine-ization' of space operations will increase the risk of fire. A safe, effective fire suppression system must be included. Every previous manned U.S. spacecraft has had some type of fire suppression capability, but these may not be the best for the station. For example, the space shuttle orbiters carry both fixed and portable Halon 1301 systems. Because of the toxicity of compounds produced when Halon 1301 reacts at high temperature with combustion products, NASA policy is to terminate the shuttle mission if a fixed system is discharged, even if the fire is extinguished.

The space station, however, must continue to function on orbit after a fire. Developing new systems, on the other hand, requires more detailed knowledge than is presently available in the areas of microgravity combustion and extinguishment. The space station will be the ideal vehicle for conducting research in this area, but the station must be protected from the beginning. The purpose of this study was to identify the best interim fire suppression alternative for the space station. A number of potentially feasible alternatives were

evaluated based upon current understanding of fire behavior in a microgravity environment.

Two scenarios were developed. The first involved a small, localized fire, and the second was concerned with either a large, module-wide fire or an explosive concentration of hydrogen gas in a module. A systems engineering framework was used. Measures of performance for the alternatives included effectiveness on different fire types, toxicity, adverse effects on the station and equipment, and cost. The Analytical Hierarchy Procedure was used to determine the best overall performers. For the localized fire scenario, carbon dioxide portable fire extinguishers were the most favorable of the alternatives. For the large fire/ explosion prevention scenario, Halon 1301 was found to be the best agent for a total flooding system.

A SYSTEMS ANALYSIS OF FIRE SUPPRESSION ALTERNATIVES FOR THE U.S. SPACE STATION

I. Introduction

The United States has been conducting manned spaceflight operations for some twenty-six years. Although there have been a number of mishaps and incidents, some with tragic consequences, NASA has never experienced a fire in space aboard a manned spacecraft.

The space station, which NASA and several international partners plan to orbit in the mid-to-late 1990s, poses many new challenges for safety planners. Among these is the threat of fire. Although careful planning and extensive use of state-of-the-art fire retardent materials will lessen the fire hazard on the station, the fact is that the potential for fire cannot be eliminated. Matthew Cole, a fire protection engineer at NASA's Johnson Space Center, states in regard to the space station: "Fire is perhaps one of the most credible threats; the most likely to occur" (4:3).

History

As stated previously, there has never been a fire in outer space aboard a manned U.S. craft. However, fires have always been regarded as a threat in space; consequently, each successive generation of spacecraft has had some provision for extinguishing fires. For example, the Mercury and Gemini spacecraft had water available from food rehydration guns while Apollo and Skylab had foam-based systems (4:3).

The fire suppression system now in use aboard the Space Transportation System (shuttle) uses Halon (Freon) 1301 in both fixed and portable systems. Halon 1301 is one of the most all-around effective extinguishing agents in existence. It does have drawbacks, however, the most significant being toxicity. In its pure or "neat" state it is only mildly toxic, but when it is applied to a fire, its by-products can be dangerous to life as well as corrosive to equipment (13:10). As a result, NASA's policy is to terminate a shuttle mission if one of the fixed systems must be discharged, even if the fire is extinguished (22:40).

NASA is concerned about the use of Halon 1301 aboard the space station and would like to determine if there is a more suitable extinguishing agent that can be used in space.

Problem Statement

Given the unique scenario and operating conditions of the space station, what type of fire extinguishing alternative is best suited for incorporation into the station fire detection and suppression system?

Methodology

A systems approach will be used in this study. Sage lists the seven steps of systems engineering, more commonly known as Hall's methodology (39:5) :

1. Problem definition
2. Value system design
3. System synthesis
4. System analysis
5. Optimization of alternatives
6. Decision making
7. Planning for action

Each of the seven steps is further defined by Kramer (20).

Problem definition: Identification of needs, alterables (variables), and constraints.

Value system design: Identification of the specific objectives and the measurables that will be used to determine the performance of each of the alternatives.

System synthesis: Conceptualization of alternatives which could satisfy the objectives.

System analysis: Estimating the performance of the alternatives with respect to the objectives.

Optimization: Reduction of feasible alternatives by discarding inferior designs.

Decision making: Ranking of alternatives and selection of one or more for further study.

Planning for action: Communicating the results.

Justification of Methodology

Figure I-1 depicts the hierarchy of subsystems within the space station system. Note that the fire extinguishing agent subsystem has no subsystems beneath it in the hierarchy. As such, it is not a traditional system, defined by Athey to be "any set of components which could be seen as working together for the overall objective of the whole" (1:12). However, each alternative that will be considered in this study does have multiple attributes. These attributes

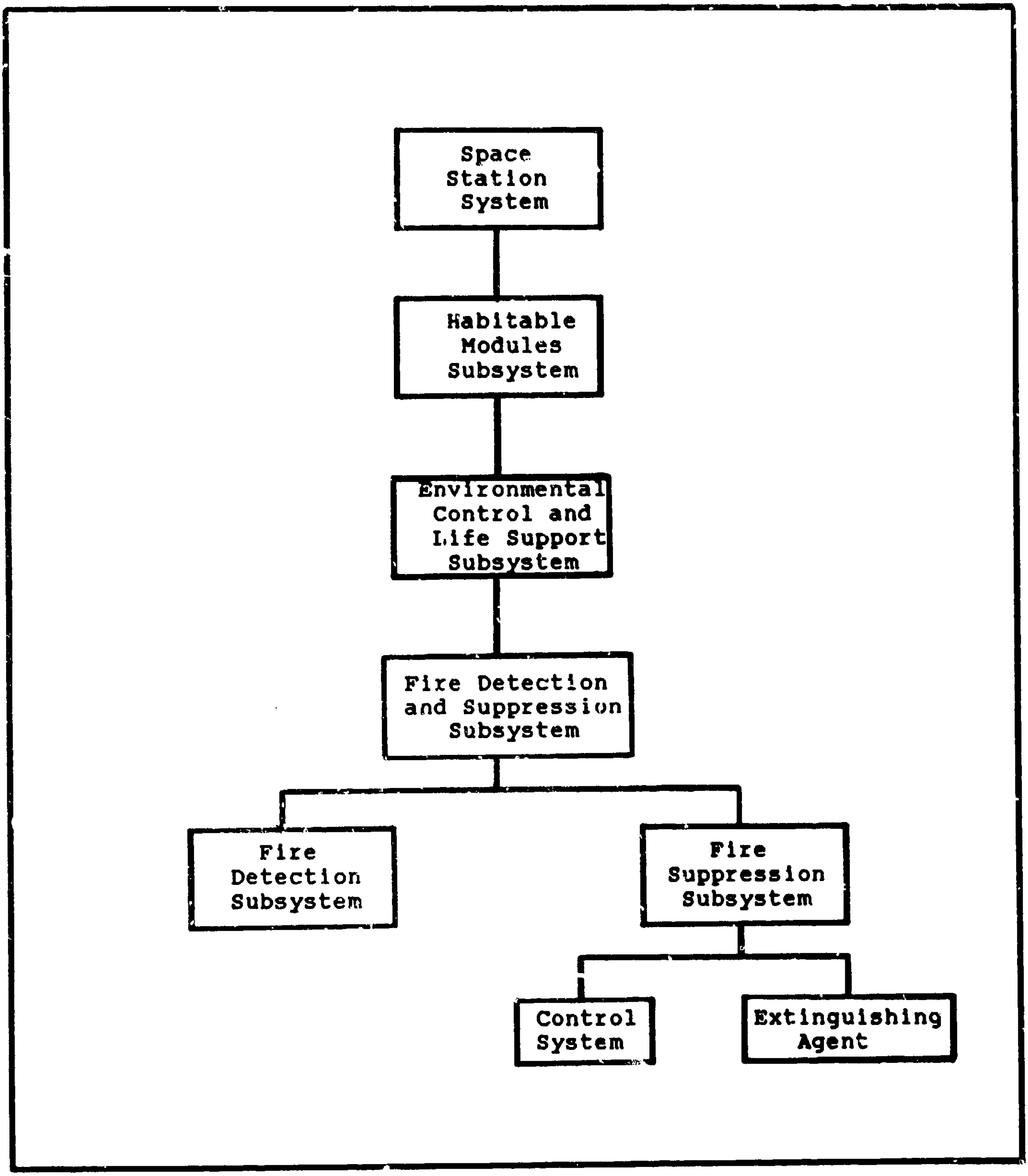

Figure I-1

Position of Fire Suppression System
Within the Space Station System Hierarchy

serve as a means by which the alternatives can be compared, hence, the alternatives can be considered to be systems. Also, the purpose of this study is not to "create" an ideal fire extinguishing agent or method, but to evaluate existing ones to find the best solution for a given scenario.

Scope

This thesis will be concerned only with existing fire safety technology, specifically, fire extinguishing agents. Additionally, class D (combustible metals) fires will not be addressed; they are an entirely different problem than the one dealt with in this study.

No attempt will be made in this thesis to analyze alternative fire detection systems. The assumption is made that the detection system is "state-of-the-art" and will provide ample warning of any fire to the space station crew.

Limitations

Only limited research has been done in the area of fire extinguishment in the space environment; consequently, any recommendation made in this study is intended only for use as an interim measure pending further research aboard the station itself.

It is important for the reader to understand that, although the author conducted a thorough literature search and consulted numerous fire safety experts, many of the judgments in this thesis, especially the ones dealing with effectiveness of various fire extinguishing agents, are somewhat subjective.

As such, the results of this work should not be taken as conclusive proof that one alternative is superior to another. The framework presented here could, however, be utilized by those tasked with making the final decision on the type of system(s) to be used on the space station.

Background

Combustion Principles. Fire, as seen through the eyes of the fire protection community, is described as "destructive burning" (13:2). A more complete definition of the combustion process, as given by Roth, is "a rapid decomposition of matter by oxidation such that heat is dissipated and gases emitted" (37:1). In order for the combustion process to be initiated, three elements must be present. These elements, which make up the familiar "fire triangle", are fuel, an oxidizing agent, and a source of ignition (32:7).

Fires are generally classified according to the nature of the fuel element of the fire triangle. Krasner provides the following definitions of fire classifications (21:22):

> Class A fires are fires in ordinary combustible materials, such as wood, cloth, paper, rubber, and many plastics.
>
> Class B fires are fires in flammable liquids, oils, greases, tars, oil base paints, lacquers, and flammable gases.
>
> Class C fires are fires which involve energized electrical equipment where the electrical nonconductivity of the extinguishing media is of importance. (When electrical equipment is de-energized, extinguishers for class A or B fires may be used safely.)

Class D fires are fires in combustible metals, such as magnesium, titanium, zirconium, sodium, lithium, and potassium.

The second leg of the fire triangle, ignition, can be broken down into three categories. They are: Electrical ignition, such as an electrical spark or arc; thermal ignition, which can be caused by heated surfaces, friction sparks, hot gases (such as open flames), and spontaneous combustion; and chemical ignition, that is, ignition caused directly by a chemical reaction (23:10).

Once the combustion process has begun, the rate of combustion and of flame propagation is strongly dependent upon the availability of oxygen (9:3). When a material burns in an environment where gravity forces are present, gravity induced convection causes the heated, lighter-than-air combustion products to rise. This, in turn, causes additional oxygen to be drawn to the flame location (29:137).

Fire Extinguishment. Once combustion has begun, it will continue until one of the following conditions is met (28:2-6):

1. The combustible material is consumed or removed.

2. The concentration of oxidizing agent is lowered to the point that it will not support combustion.

3. The combustible material is cooled to below its ignition temperature.

4. The flames are chemically inhibited.

All fire suppression agents fit into one of the four general categories listed below (13:10):

1. Agents that disturb the burning material.

2. Agents that prevent oxygen from reaching the flame (smothering agents).

3. Agents that remove the heat from the fire (cooling agents).

4. Agents that chemically alter the combustion process. (also referred to as chain-breaking agents).

For example, sand will disturb burning material, while water extinguishes fires by removing heat. Some extinguishing agents work in more than one way to put out flames--carbon dioxide acts primarily as a smothering agent, but it also has a cooling effect. Halogenated hydrocarbons (halons) and dry chemical agents primarily act as chemical flame disruptors, but the former also cools to some extent while the latter can also act as a smothering agent (28:13-23,13-28).

Effects of Zero Gravity. Much remains to be investigated in this area. Some research has been done aboard aircraft, in special "drop towers" at NASA's Lewis Research Center, and aboard Skylab (13:6). This research has indicated that the absence of gravity-induced convection can have an effect on the combustion process. Figure I-2 shows the behavior of a methane flame in the Lewis drop tower. The flame was initiated in normal gravity conditions prior to the drop. While under 1-g conditions, the flame fluctuated due to convection. After microgravity was initiated, the flame initially decreased, then increased to nearly the 1-g level. Note the lack of fluctuation of the flame in microgravity (due to lack of convection). In some cases, the flame was seen to self extinguish before its length stabilized. One theory behind this is that

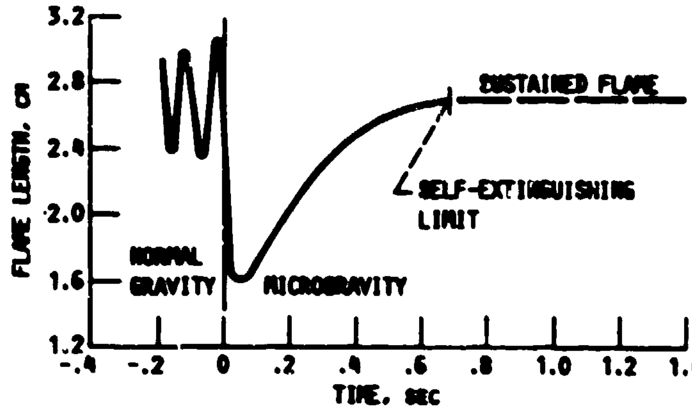

Figure I-2

Typical Histories of Low Gravity Methane-Air Flames in NASA Lewis 2.2 sec Drop Tower (13)

because of the absence of convection, the products of combustion are not carried away and cause a blanketing effect around the fire, preventing oxygen inflow (13-7).

In reference to the above experiments, Friedman and Sacksteder note:

> While these observations imply that the fire hazards may be reduced in microgravity compared to normal gravity, there are other factors that can cancel this apparent safety factor. Spacecraft ventilating systems superimpose forced convection, which may enhance low-gravity flame spread...Certain materials (Kimzey observed this with Nylon) tend to boil and scatter when burning in low gravity...Microgravity flames, while cooler than corresponding normal-gravity flames, may be more radiant due to the concentration of soot particles. This could increase the dangers of flashovers and fire spread to adjacent surfaces through radiant heat transfer (13:8).

The effects of forced ventilation may very well negate any tendency for burning material to self-extinguish in a zero gravity environment. A pre-Skylab study done for NASA showed that forced ventilation of 50 feet per minute in zero gravity would cause a cloth specimen to burn exactly as it would in one-g conditions (41:9).

The effects of zero gravity upon open fires must be taken into consideration. Unless an object is physically connected to the station, it will float. Burning liquids, instead of pooling, could easily separate into numerous flaming globules. This could complicate the job of extinguishing the fire.

Microgravity conditions can also impact the effectiveness of fire extinguishing agents. For example, Roth notes that smothering agents (those that prevent oxygen from reaching the combustion area) will disperse more freely under zero gravity conditions, possibly rendering them less effective (37:90). Roth also notes that liquids will not settle on a flame area in zero gravity, perhaps making a stream of water a less effective agent (37:91).

Space Station

A review of a few of the unique aspects of the space station is necessary at this point to provide the reader with more insight regarding the problem.

Module Arrangement. The baseline configuration of the space station will consist of four habitable modules and a logistics module (Fig I-3). The United States will contribute two modules, one of which is a laboratory, the other a

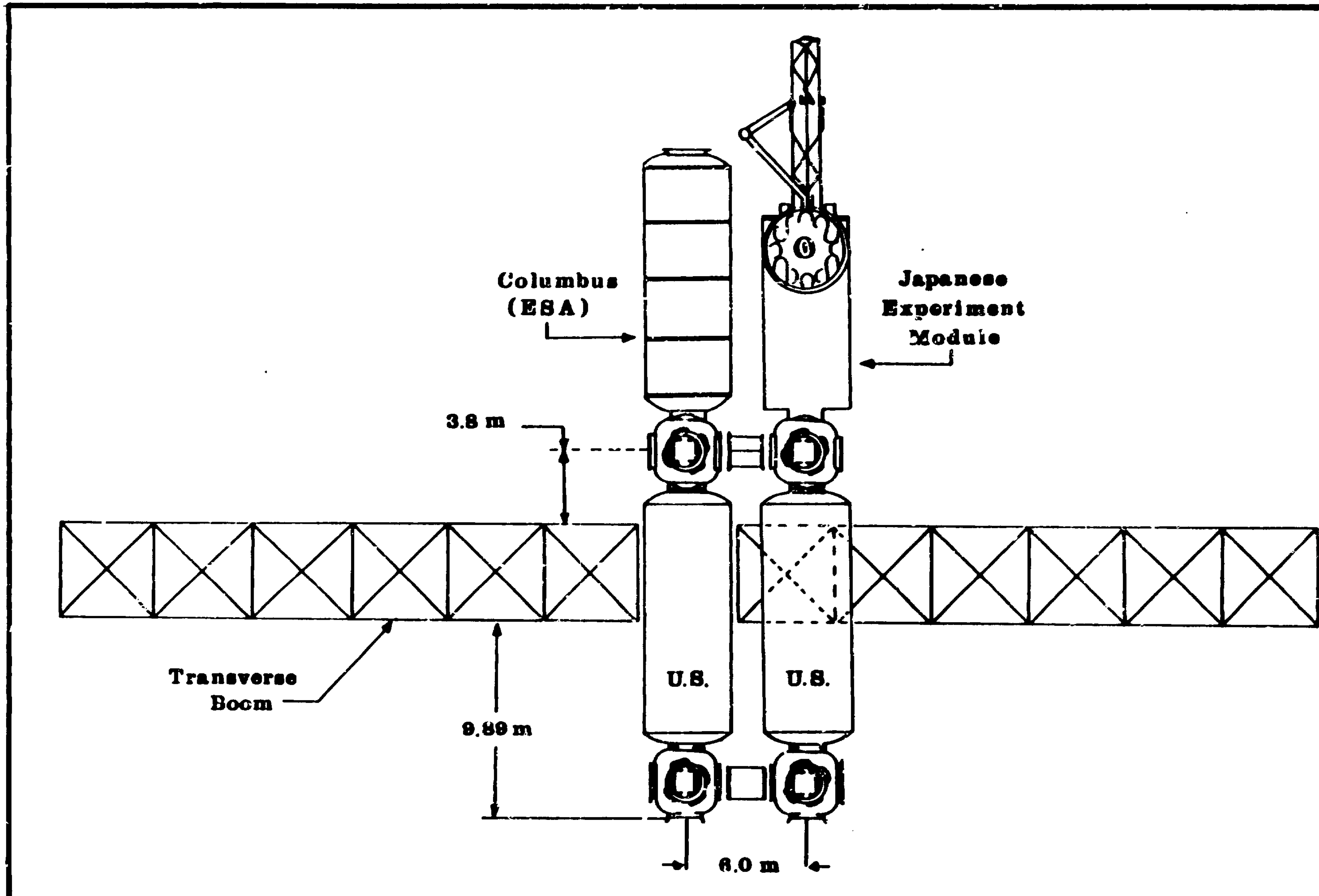

Figure I-3

Space Station Module Arrangement (4)

habitation module. The European Space Agency (ESA) will have one laboratory module, as will the Japanese (15). The modules will be connected by a series of airlocks which will allow a burning or contaminated module to be sealed off from the remainder.

ECLSS. Both U.S. modules will be equipped with dual environmental control and life support systems (ECLSS) which will perform a number of functions, including closed-loop water recycling and continual regeneration of the module atmosphere. These systems will basically support the entire station, as the international modules will not have full ECLSS capability (36). Even if three of the four ECLSS systems were rendered inoperative, the fourth would support an eight man crew in a degraded mode (36).

Atmospheric Regeneration. The atmospheric composition will be basically identical to the earth's, i.e., approximately 21 percent oxygen and 79 percent nitrogen, with cabin pressure set at 14.7 psi (34:299). Extra nitrogen (to enable repressurization of a depressed module) will be stored in the form of high-pressure (3000 psi) gas in tanks external to the modules. Atmospheric oxygen will be generated through the electrolysis of water. Hydrogen, which is a byproduct of this electrolysis, will be combined with carbon dioxide removed from the atmosphere to produce more water (33).

Regenerated air is supplied to the modules through ten ceiling-mounted air diffusers which provide a ventilation path from the ceiling to the module floor. The average airflow rate in the cabin is 20 feet per minute with a maximum of 150 feet per minute near the diffusers (5:72).

Carbon dioxide produced by the station occupants will be continually removed from the atmosphere and combined with hydrogen to form water. A filtration subsystem will remove particulate matter from the cabin atmosphere (33). A trace contaminant control subsystem will be able to remove a number of expected atmospheric contaminants, including carbon monoxide, chloroform, and ethyl alcohol (33).

Fire Risks. The basic concept of a long term manned orbiting laboratory presents a number of fire hazards. Extensive laboratory experiments will be conducted, many possibly requiring the use of hazardous materials and processes (4:1). Some experiments will be conducted in a high temperature furnace (17:18).

Aside from laboratory work, other conditions aboard the space station will present new risks of fire. De Meis notes:

> There will be different housing conditions with light industrial work such as repair shops doing soldering and metal work, creating possible ignition sources and flammable waste. Laundry will have to be done, and dryers are a source of heat and lint. Even recreation has to be investigated. Food preparation will present new risks of fire (7:27).

As its first line of defense against fire, NASA will use careful control of materials allowed on the station, as well as strict safety procedures. However, there is a possibility that complacency, however slight, can affect the behavior of astronauts in long-duration missions. In the NASA/USSR Academy of Sciences Project on the Foundation of Space Biology and

Medicine, it was noted that a spacecraft tends to take on more of the characteristics of a home as mission duration increases (41:10).

A safety analysis report prepared by a NASA contractor did not identify specific fire hazards or the probabilities of occurrence of different fire types (30). However, it appears that Class A, B, and C fires could all occur on the station and must not be considered self-extinguishing, especially due to the forced ventilation which will be present. The afore-mentioned report did, however, point out that the presence of hydrogen from the ECLSS water electrolysis process creates the potential for a catastrophic explosion of a module and possible destruction of the entire station (30:B-35).

Summary

The space station program presents many new challenges to those charged with ensuring the safety of the personnel and equipment on board. Through careful planning and operation, NASA hopes to avoid the occurrence of an onboard fire. However, the worst possible case must be taken into consideration, so the possibility of a catastrophic fire or even an explosion must not be overlooked. Although some research has been conducted in the area of microgravity combustion and fire extinguishment, more research will be necessary to find ideal methods to combat fires in space. The space station will be an ideal setting to conduct this research; however, in the interim, the station itself must be protected. The problem is to find the best interim solution using current fire protection technology. The next section will outline the criteria for candidate solutions.

II. Measures of Effectiveness

Introduction

This chapter will lay the foundation for the remainder of the study. The second step of Hall's methodology, value system design, will be applied. The end result will be the definition of the measures of effectiveness, the criteria by which alternative solutions will be compared in a later chapter.

Scenarios

At this point, the problem of fire extinguishment can be addressed more effectively by considering two separate possible scenarios for a fire on the space station:

(1) a small, localized fire

(2) a large, module-wide fire or a leak of explosive gases into the module atmosphere

Localized Fire. These could be "trash can" fires, galley fires, equipment rack fires, etc., and could be class A, B, or C in nature. They could involve burning surfaces or even burning material that is floating in the cabin; regardless, they are relatively small and are confined to one area. They might be extinguished either by a hand-held fire extinguisher, or, in the case of electronic equipment in racks, by a centralized distribution system piping agent only to the affected rack. For simplicity's sake, this study assumes the use of hand-held extinguishers only. After extinguishing the fire, astronauts could seal off the module and remain inside if necessary, wearing breathing packs until any smoke or atmospheric contaminants (carbon monoxide, etc.) were removed by the ECLSS.

Large Fire/ Explosion Prevention. This scenario could involve a fire that had gone undetected for a considerable time and had spread significantly, although such an occurrence would be unlikely where fire retardent materials and a good fire detection system are involved. Another possibility might involve the spillage of a flaming liquid which could spread quickly throughout the cabin. Perhaps the greatest threat could come from leakage of the volatile gases associated with the operation of the ECLSS. Methane may be present, depending upon the final design of the system, but hydrogen will definitely be produced and is certainly the more volatile of the two. An explosion can occur with as little as a four percent concentration of hydrogen in the atmosphere, and only 0.1 millijoules of energy would be required to trigger the explosion (30:B-35).

In this scenario, astronauts would preferably abandon and seal off the module immediately after detection of hydrogen in the atmosphere or after the start of a large scale fire. Then, they would actuate the suppression system and remove power from the affected module ventilation system. After the fire was extinguished or the module atmosphere was inerted, the module would be vented to space. This would allow either the dispersal of the explosive gases or the elimination of all toxic combustion byproducts. Kimzey has said that the materials used in spacecraft would produce "several thousand" unsafe compounds in a large scale fire (19:3). Even though the station's ECLSS will have a trace contaminant control system, this system will not be designed to handle large scale post-fire toxic gas removal (36). Venting smoke and soot to space might cause some exterior contamination on windows, sensors, and so forth (19:16). However, this would be preferable to endangering the crew.

Value System Design

As stated previously, Kramer defines the value system design phase as identification of the specific objectives and the measurables that will be used to determine the performance of each of the alternatives. In this section, the objectives will be drawn from the problem statement and the scenario,then will be further refined into the measures of effectiveness.

Objectives. Athey defines objectives as "the goals or results that the decision-maker wants, or should want, to attain in regard to a particular system" (1:19). The objectives can form a hierarchy with the overall objective (need) at the top, as shown in Figure II-1.

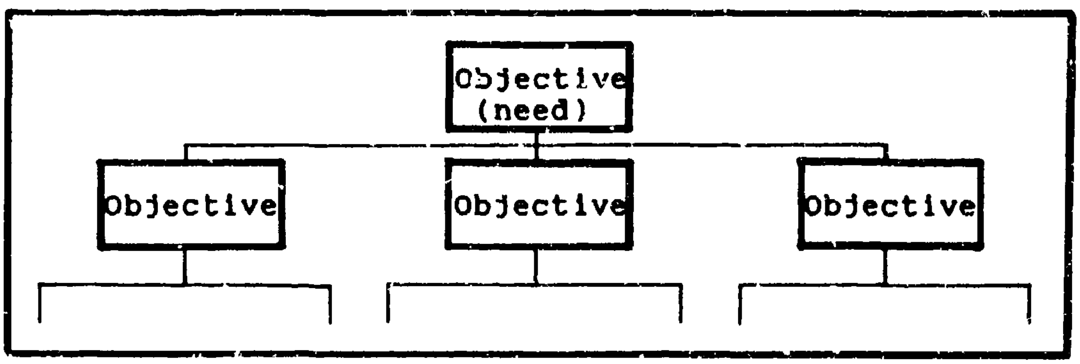

Figure II-1

Typical Objective Hierarchy (39:27)

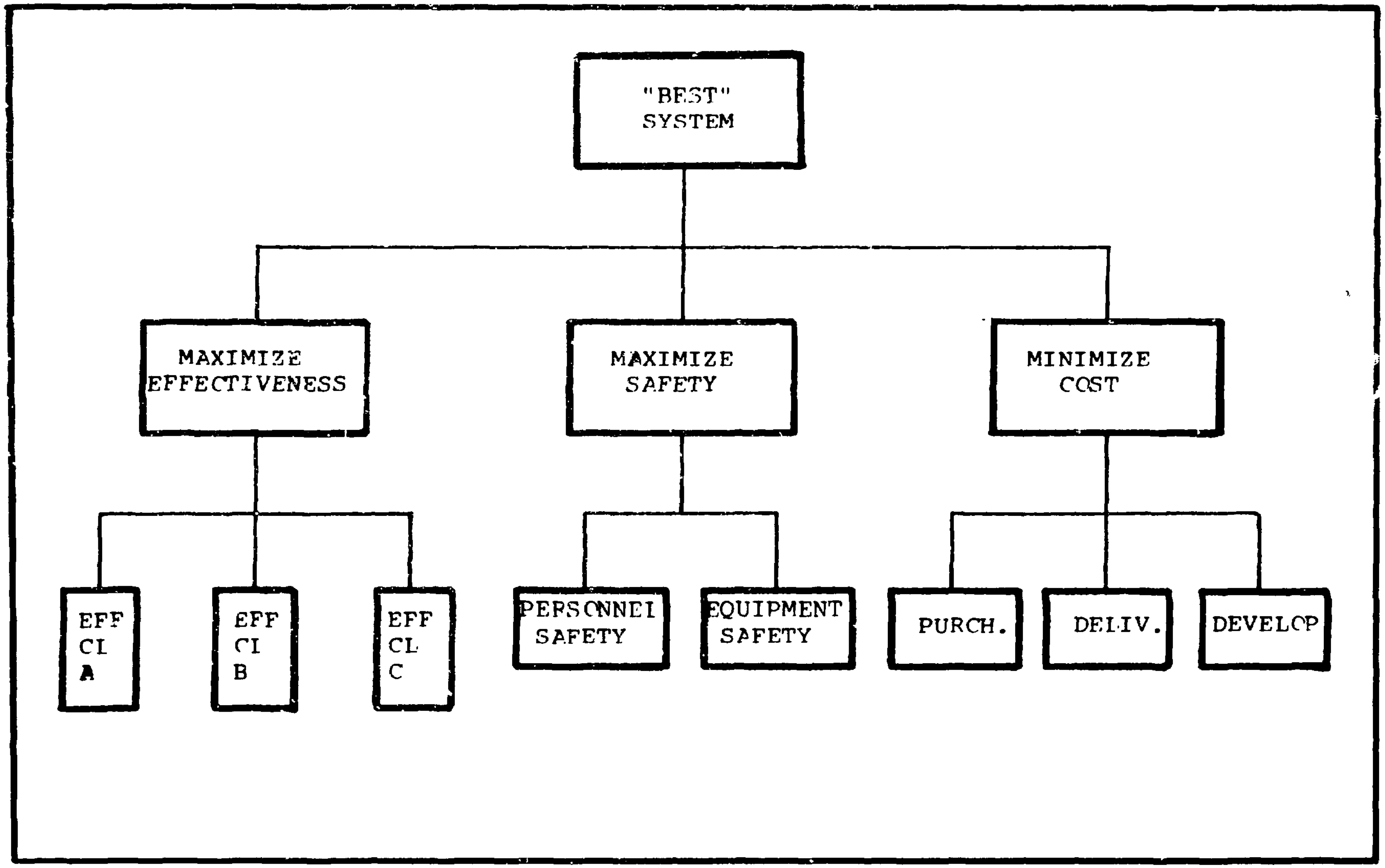

Figure II-2

Objective Hierarchy - Localized F... Scenario

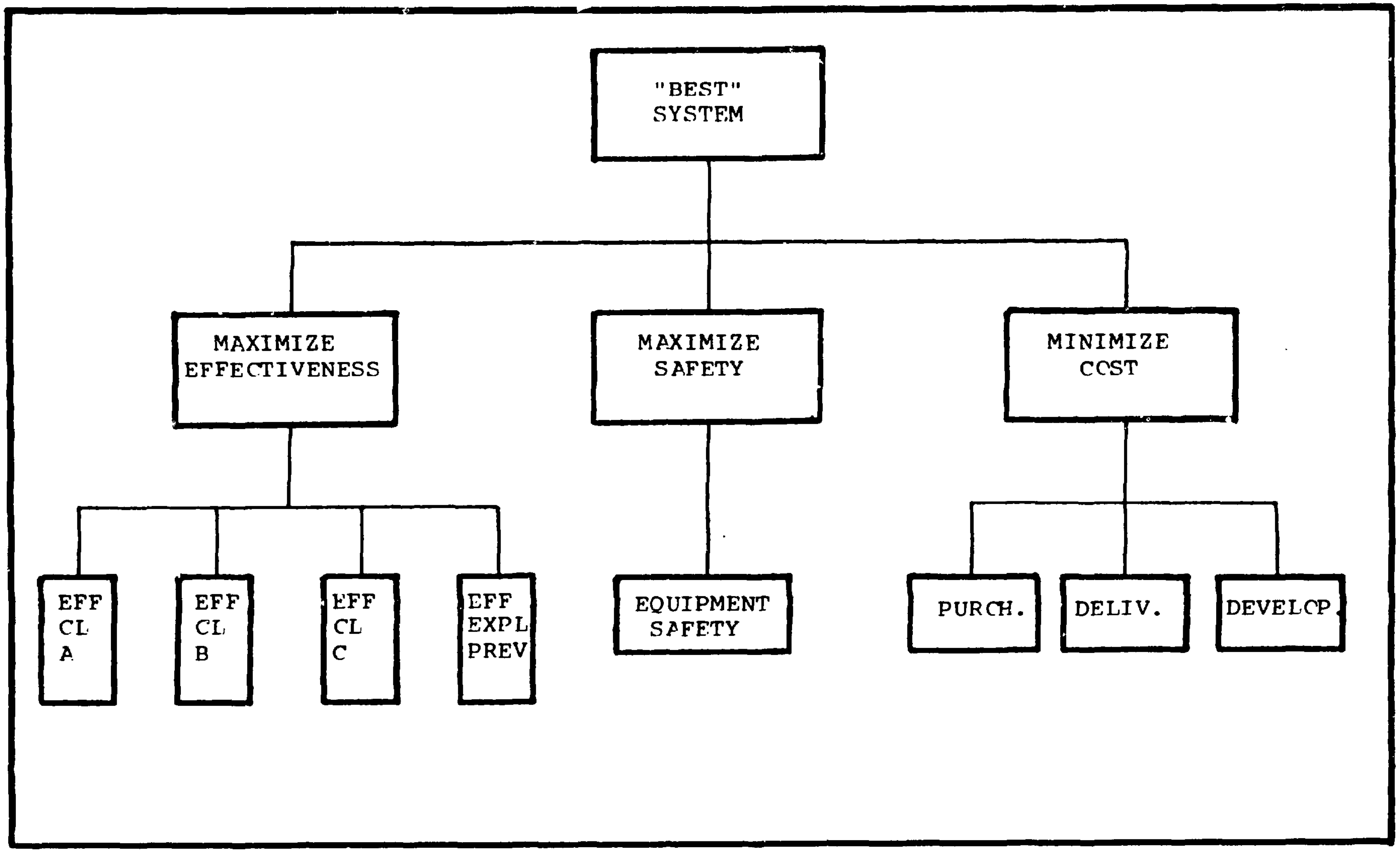

Figure II-3

Objective Hierarchy - Large Fire/Explosion Prevention Scenario

<u>Localized Fire Scenario</u>. Figure II-2 depicts the hierarchy of objectives for this scenario. The first objective is to maximize effectiveness. The three sub-objectives are to maximize effectiveness against the types of fires that may occur on the station, specifically, class A, B, and C fires.

Safety is of the utmost importance in any manned space-flight operation; as a result, maximum safety in the use of a fire extinguishing agent is desired. Obviously, there is concern over the safety of the personnel on board, but the equipment and facilities on the station must be considered also. Each module will be worth hundreds of millions, if not billions, of dollars and will contain a large quantity of extremely sensitive and expensive laboratory equipment and experimental packages. The sub-objectives are to minimize adverse affects on personnel and on hardware that are attributable to the extinguishing agent.

The third and final main objective is to minimize cost. The projected cost of the space station program continues to escalate, so it is important to hold costs to a minimum where it is feasible to do so. Three sub-objectives can be defined here. First, the cost of the fire extinguishing system itself should be minimized. Next, the cost of delivering the system to the station should be minimized. A study done for NASA indicated that the cost of delivering materials to the space station via the shuttle will be approximately $2220 per pound (5:97). Last, and more abstract, is the concept of technical readiness. Any system which has not been operational in space will require a certain amount of developmental work before it can be space certified. The three sub-objectives, again, are to minimize system cost, minimize delivery cost, and maximize technical readiness.

Large Fire/ Explosion Prevention Scenario. The hierarchy of objectives for this scenario is depicted in Figure II-3. Many of the objectives and sub-objectives in this scenario are identical to those in the localized fire scenario. However, because of the assumptions made for this scenario, there are some significant differences.

Again, the first objective is to maximize effectiveness. As in the localized fire scenario, maximum effectiveness is desired against class A, B, and C fires. In addition, maximum effectiveness in inerting a potentially explosive atmosphere is desired.

The second objective is to maximize safety. In this scenario, it is assumed that personnel leave the module prior to activating the fire suppression system and will not be in danger. An additional factor, though, is the possible structural effects of introducing large quantities of agents into a module. Therefore, the two sub-objectives are to minimize adverse effects on interior equipment and minimize adverse effects on the module structure.

The final objective is to minimize cost. All of the sub-objectives identified in the localized fire scenario are still applicable here.

Measures of Effectiveness. The objectives defined in the previous sections represent all of the areas in which candidate solutions must be compared. In order to enable the comparisons to be made in a later chapter, the lowest level objectives in Figures II-2 and II-3 must first be translated into the measures of effectiveness, which can be either quantitative or qualitative. Figures II-4 and II-5 depict the measures of effectiveness along with the objective hierarchies for both scenarios.

It should be noted that the breadth of the rating scale (five-point, three-point, etc.) for each individual measure of effectiveness is purely arbitrary and was selected for the convenience of the author.

Localized Fire Scenario. The first objectives to be dealt with are the ones related to effectiveness. Effectiveness of a particular agent against class A, B, and C fires is difficult to quantify, so a five point qualitative scale of one through five will be used. A rating of "one" will indicate a relatively ineffective agent, while a rating of "five" will indicate that a fire would be extinguished quickly and permanently.

For the objective of personnel safety, toxicity of the agent or its by-products will be the measure of effectiveness. A three-point scale of one through three will be utilized. A rating of "one" indicates that the agent or its byproducts can be extremely dangerous regardless of the quantity used. A "two" rating indicates an agent which is somewhat toxic but not particularly dangerous when used in the quantity required

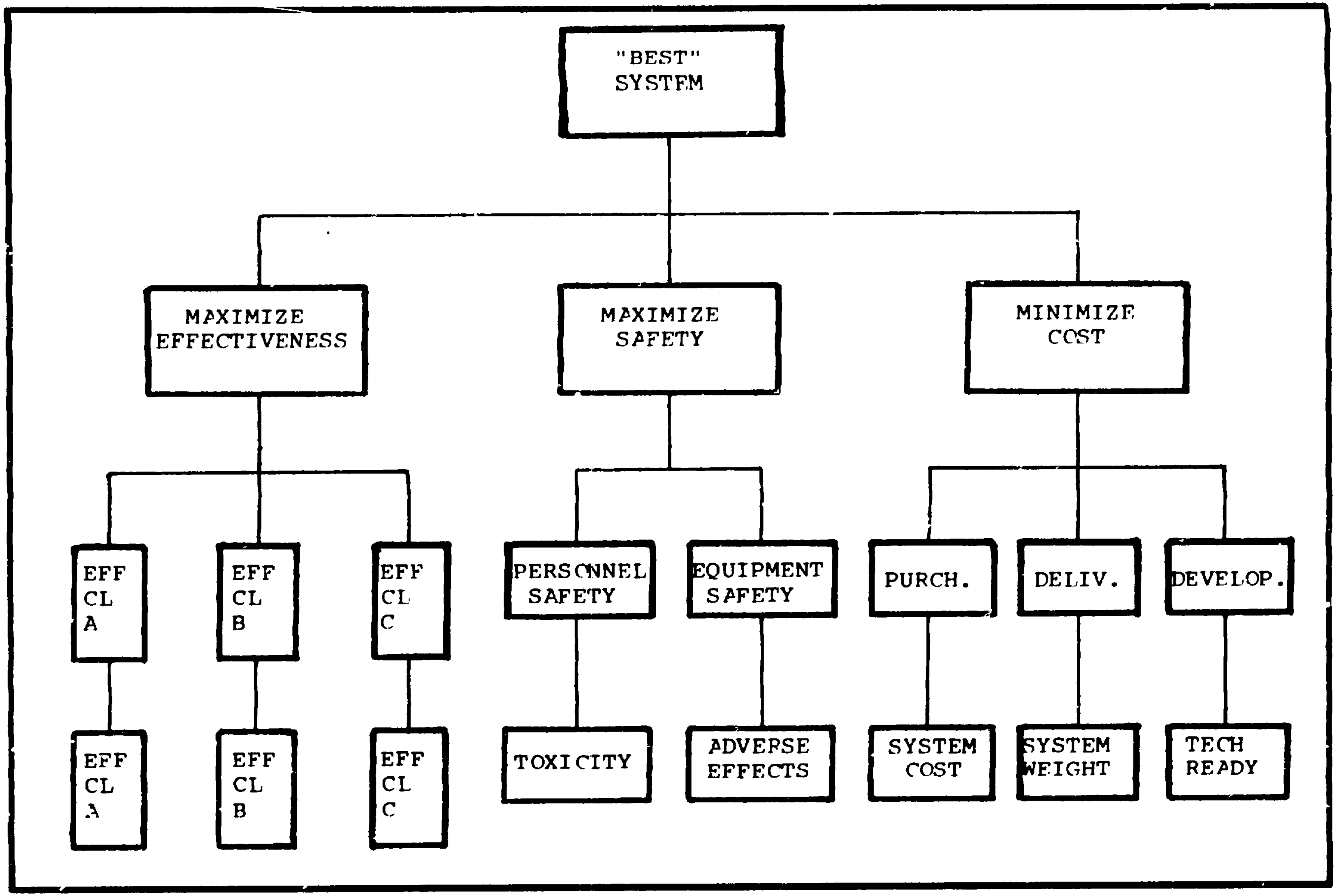

Figure II-4

Objective Hierarchy with Measures of Effectiveness
Localized Fire Scenario

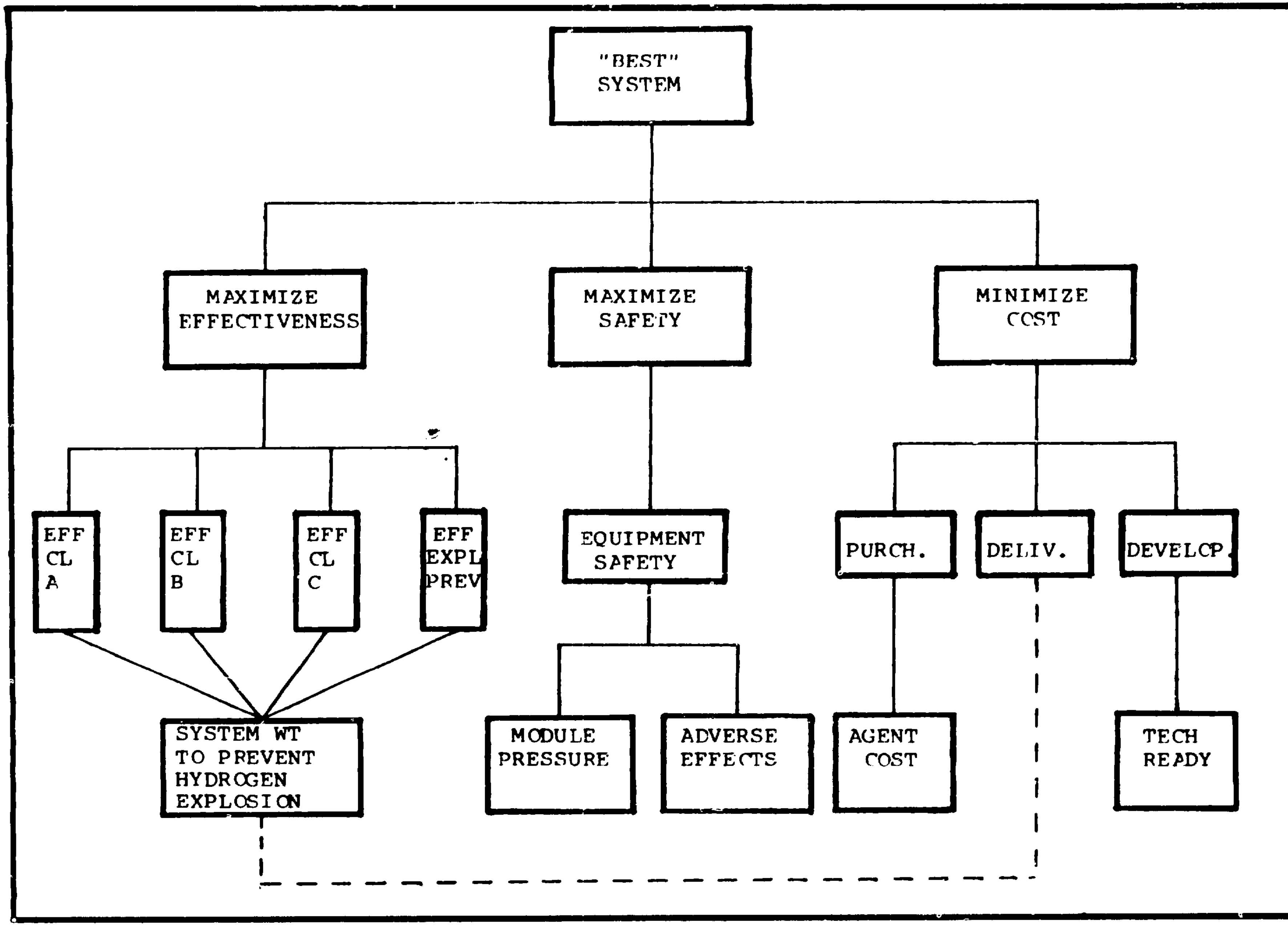

Figure II-5

Objective Hierarchy with Measures of Effectiveness
Large Fire/ Explosion Prevention Scenario

for a localized fire. A "three" indicates either that the agent is completely non-toxic, or that it is mildly toxic but can be effectively removed from the module atmosphere by the ECLSS.

Adverse effects on equipment can be a result of corrosion caused by an agent or its byproducts, or a result of residue left by an agent (which can interfere with electronic components, etc.). A three-point subjective scale will be used to indicate adverse effects of an agent on station equipment. In this case, a "one" rating indicates that the agent could have lasting adverse effects. A "two" will denote an agent that could have temporary effects, but can be effectively cleaned up or neutralized. A "three" will indicate an agent which should have no adverse effects on equipment.

For the objective of minimizing system cost, the cost in dollars of comparative hand-held fire extinguishers will be used. For delivery cost, the weight of an extinguisher will be the measure of effectiveness.

Finally, technical readiness must be measured. The measure of effectiveness will be "yes/no". "Yes" will indicate that the agent is currently in use in a portable extinguisher in a U.S. spacecraft. A "no" will indicate otherwise.

<u>Large Fire/ Explosion Prevention Scenario.</u> To measure the effectiveness of an agent in a situation where it will flood the entire module, the quantity of agent necessary to cause the atmosphere to be inert will be used. The worst case aboard the space station would be an explosive mixture of

hydrogen in the atmosphere. The measure of effectiveness, therefore, will be the weight of agent that is required to prevent a hydrogen explosion in the module (less agent is better).

Adverse effects on the module structure can be treated as a function of atmospheric pressure inside the module. At the current time, the module pressure limits have not been decided upon (26). It is clear, though, that a module built to withstand higher pressures will cost more than one with a weaker structure. If the pressure resulting from the discharge of a fixed system inside a module was greater than the design structural limit, the structure could be weakened or could fail entirely. Therefore, the measure of effectiveness will be the total atmospheric pressure inside the module after it is totally flooded with extinguishing agent.

Adverse effects of an agent on station equipment will be measured the same way as in the localized fire scenario, on a three point scale. A "one" rating indicates that the agent could have lasting adverse effects. A "two" will denote an agent that could have temporary effects, but can be effectively cleaned up or neutralized. A "three" will indicate an agent which should have no adverse effects on equipment.

The measure of effectiveness for purchase cost will be the cost of the amount of agent required to protect a module from a hydrogen explosion. It is impractical to estimate the cost of other system components (storage bottles, control systems, etc.), so it will be assumed to be constant for all possible alternatives.

Delivery cost will depend upon the total weight of the system. System weight is the sum of the weight of agent required to prevent a hydrogen explosion in a module and the weight of the storage container required for the agent. All other system components, such as plumbing and electrical circuitry, are assumed to be essentially identical for all agents. As the MOE here is similar to the one for agent effectiveness, the two will be combined. Therefore, the combined MOE for effectiveness and delivery cost will be the system weight.

Finally, the measure of effectiveness for technical readiness will be identical to that for the localized fire scenario. The measure of effectiveness will be "yes/no". "Yes" will indicate that the agent is currently in use in a fixed extinguishing system aboard a U.S. spacecraft.

Summary

In this chapter, two possible fire scenarios for the space station were identified: Localized fire and large scale fire or possible explosion. The objectives for each scenario were defined and then translated into measurable form, the measures of effectiveness. These MOEs will be utilized in a later chapter when the performance of alternatives will be measured and compared.

III. System Synthesis

In this phase of a systems analysis, as many feasible alternatives as possible are to be generated. Kramer defines a feasible alternative as one which: (1) is potentially technically realizable in the time frame of interest; (2) is not in violation of any constraints; and (3) meets the specified objectives to some degree (20). In this particular study, it is possible that, because of the two different scenarios and their accompanying constraints, an alternative may be feasible for one or both scenarios. As a result, a short background on each alternative will be presented first, then scenario constraints will be applied to determine which of the alternatives to evaluate for each scenario.

Alternatives

Seven alternatives will be discussed in this section. They are:

(1) Carbon Dioxide (CO2)
(2) Nitrogen (N2)
(3) Multipurpose Dry Chemical (D CHEM)
(4) High Expansion Foam (FOAM)
(5) Halon 1301 (H1301)
(6) Deionized Water (H2O)
(7) Vent Module to Space (Cabin Dump)

Carbon Dioxide. CO2 extinguishers have been widely used in a number of applications for many years. CO2 normally exists in gaseous form and is heavier than air. However, it liquefies under high pressure; at 70 degrees F it liquefies at approximately 850 psi (12:4). When liquid CO2 is released from a storage cylinder, the rapid expansion of the liquid to gas causes its temperature to drop to minus 110 degrees F (28:13-18). A small portion of the liquid CO_2 does not change phase and emerges in the form of dry ice crystals. These crystals provide somewhat of a cooling effect on a fire, although CO_2 extinguishes primarily by smothering, or displacing oxygen (28:13-18).

Nitrogen. N_2 is an inert gas that has not seen wide use as a fire extinguishing agent, although it is currently used in some military aircraft (a portion of the C-5 Galaxy's fire suppression system uses N_2). Probably its primary use is to provide an inert atmosphere to prevent fire or explosion in unmanned environments (such as fuel tanks or cabinets housing electrical equipment). N_2 is slightly lighter than air; of course, air contains approximately 79 percent N_2. N_2 can be stored as a high pressure gas or as liquid nitrogen, which has a boiling point of -195.8 degrees C (24).

N_2 would extinguish fires primarily by displacing oxygen. Its cooling effect would probably be minimal when stored in gaseous form, but liquid nitrogen might be expected to provide some cooling, perhaps similar to that provided by CO_2.

Multipurpose Dry Chemical. The term "dry chemical" can refer to one of a number of powdered mixtures widely used to combat liquid and electrical fires (class B and C) (28:13-27). "Multipurpose" dry chemicals, which are of a monoammonium phosphate base, were first developed in 1960 (28:27). Multipurpose agents are also suitable for use on ordinary combustibles (class A) (28:13-27). Their primary means of extinguishing fires is through "chain breaking", that is, chemical interference with the combustion process. Also, when multipurpose agents contact burning material, they melt and effectively seal off the combustion zone from oxygen (28:13-28).

High Expansion Foam. Foam extinguishers were used aboard the Apollo and Skylab spacecraft. In the late 1960's, high expansion foam was evaluated for possible use in the short-lived Air Force Manned Orbiting Laboratory program (3:1). By injecting air into the liquid foam solution, an expansion ratio of 300:1 could be achieved (18:165). The primary mode of extinguishment is smothering of the fire; however, the liquid solution also exhibits a cooling action (28:13-13).

Halon 1301. Halon 1301 is a member of a group of compounds known as halogenated hydrocarbons, known for their effectiveness in combating fires. Halon 1301 (chemically known as bromotrifluoromethane, or $CBrF_3$) is currently utilized aboard both the space shuttle and Spacelab in both fixed and portable extinguishing systems (42). It is the most favorable of the halons in terms of toxicity and corrosion potential (37:93). At room temperature (70 degrees F), Halon 1301 is a heavier-than-air gas, but it liquefies under a pressure of approximately 200 psi; 1301 storage bottles are normally supercharged with nitrogen to insure that all the agent will be expelled from the container (28:13-22). The mechanism by which Halon 1301 extinguishes flames appears to be primarily chemical inhibition. However, it does also have cooling and smothering effects (12:10).

Deionized Water. Water is probably the most effective substance known for extinguishing class A fires, especially those that are deep seated (smoldering). However, in its natural state, water contains a number of impurities which can make it conduct electricity (28:13-3). Deionized water, which is created by passing distilled water through an ion exchange resin, has a much higher resistance (10^7 ohm-cm versus as little as 10^3 ohm-cm from ground water)(24, 28:13-4). The U.S. Navy has conducted tests to determine the feasibility of using deionized water to combat electrical fires aboard submarines. Although the test results were not made available, the results apparently were favorable (14). The primary extinguishing mechanism for water is cooling of the burning material, although the resulting steam also has a smothering effect (28:13-3).

Vent to Space. Each space station module will be equipped with valves which will enable the module atmosphere to be vented to space in an emergency (5:106). This action would, of course, extinguish a fire by removing the oxygen necessary for combustion. This option was not very practical in earlier spacecraft since the astronauts could not survive in an unpressurized cabin (unless they were wearing pressure suits at the time). However, in the space station, crewmembers can abandon the affected module and seal it off.

Preliminary Evaluation

Localized Fire Scenario. Only one constraint exists: Cabin dump is not an option for this scenario. The other six alternatives will be evaluated in the following chapter.

<u>Large Fire/ Explosion Prevention Scenario</u>. There is one constraint for this scenario: Since the most probable large scale threat is a hydrogen explosion in a module, candidate alternatives must be able to effectively inert the module atmosphere to prevent such an occurrence. The inerting properties of CO_2, N_2, and Halon 1301 are well documented. Water vapor (steam) does have some inerting capability; however, generation of a sufficient quantity in any reasonable amount of time would be impractical. No data could be found to indicate that either dry chemicals or high expansion foam possesses any potential to inert a hydrogen contaminated atmosphere.

Venting the module atmosphere to space would certainly be one method for inerting the module. However, one potentially critical factor stands out: time. Flooding a module with the required concentration of N_2, CO_2, or Halon 1301 might take on the order of a few seconds,depending on the characteristics of the dispensing system. In contrast, complete evacuation of a module's atmosphere could take as much as 5-6 minutes (36).

Summary

Seven potential alternatives were presented in this chapter. These alternatives were then evaluated against the scenario constraints to determine which alternatives would remain in contention. The following alternatives will be evaluated further in the next chapter:

Localized Fire Scenario

CO_2
N_2
Multipurpose Dry Chemical
High Expansion Foam
Halon 1301
Deionized Water

Large Fire/Explosion Prevention Scenario

CO_2
N_2
Halon 1301

IV. Analysis of Alternatives

The previous two chapters have been devoted to development of the framework necessary to approach the problem in a logical manner. The next two chapters contain the information that, when applied, will result in the identification of the "best" solution (given the limitations of this study).

The measures of effectiveness derived in Chapter II will allow the alternatives to be properly evaluated with respect to the objectives. In some instances, sufficient experimental or theoretical data exists to allow models to be built and objective judgments to be made. In other instances, the judgments may be highly subjective due to lack of experimental or operational data.

Localized Fire Scenario

Effectiveness (Class A fires). A five-point rating scale is used; a "one" rating indicates a relatively ineffective agent and a "five" rating indicates that the agent would extinguish a fire quickly and permanently.

Carbon Dioxide (CO_2). CO_2 extinguishes primarily by keeping oxygen away from the combustion zone. It would probably be quite effective for extinguishing surface fires. However, for deep-seated , smoldering fires, it is relatively ineffective. It does not possess much cooling capacity, and, as the average discharge time for a portable CO_2 extinguisher is only 8-15 seconds, it would not exclude oxygen from the embers for long unless the fire was in an enclosed area;

reignition is possible (16:54, 28:13-18).

Rating assigned: 3

Nitrogen (N2). No literature could be found which discussed the properties of N2 as an extinguishing agent. However, it would probably extinguish by excluding oxygen,similar to CO2. A hand-held extinguisher would use gaseous N2, which could not be expected to provide any cooling. It would likely be completely ineffective against deep-seated fires.

Rating assigned: 2

Multipurpose Dry Chemical. Dry chemical extinguishes by chemical action on the flames and by smothering. The smothering action might be affected by zero gravity, as particles could bounce off the combustion area instead of melting and providing a hard shell around the fire. As such, effectiveness against deep-seated fires may not be great.

Rating assigned: 3

High Expansion Foam. Foam extinguishes by smothering and also has a cooling effect. In addition, it can adhere to burning material (4:9). As a result, it would probably be effective on deep-seated fires. Its effectiveness on floating burning material would be dependent upon the nozzle design, as it is cohesive and does not spread well (40:1).

Rating assigned: 4

Halon 1301. Halon 1301 extinguishes by chemical inhibition and also has a slight cooling effect. A five percent concentration Halon 1301 in air will easily extinguish ordinary combustibles (11:37). It is not, however, very effective against deep-seated fires unless at least a ten percent concentration can be maintained in the combustion zone for at least ten minutes (10:38).

Rating assigned: 3

Deionized Water. Water, with its cooling action, can be highly effective against class A fires, whether they be surface or deep-seated fires. In zero gravity, its effectiveness might depend upon the absorbency of the burning material; water droplets could ricochet off of a nonabsorbent burning surface (37:91). Like foam, with a good nozzle design, it could be effective against floating, burning debris.

Rating assigned: 4

Effectiveness (Class B fires). The assumption is made that burning liquids will be in the form of floating globules. The same rating scale used for class A effectiveness is used here.

CO2. CO2 is very effective against class B fires, second only to Halon 1301 and dry chemicals (28:13-23). Its gaseous nature would allow it to easily envelop and extinguish suspended globules of burning liquid.

Rating assigned: 4

N2. N2 might work in a manner similar to CO2 against class B fires, since both agents extinguish primarily by smothering. However, research turned up no conclusive evidence concerning its effectiveness. As a subjective judgment, it is given a somewhat lower rating than CO_2.

Rating assigned: 3

<u>Multipurpose Dry Chemical</u>. Dry chemical is highly effective on class B fires, more effective than CO_2 and about the same as Halon 1301 (28:13-27). Due to the small particle size (10-75 microns), dry chemical should have little difficulty enveloping globules of flaming liquid (28:13-27).

Rating assigned: 5

<u>High Expansion Foam</u>. Under ordinary circumstances, foam is very effective on class B fires (28:13-12). However, in zero gravity, cohesive foam would probably be ineffective against widely dispersed flaming drops of liquid.

Rating assigned: 2

<u>Halon 1301</u>. Halon 1301 is extremely effective when used on class B fires (28:13-23). Its gaseous nature would allow it to adequately envelop floating liquid globules.

Rating assigned: 5

<u>Deionized Water</u>. In a one-g environment, water sprays have been tested with some success on liquid fires (8:46). However, in zero-g, their effectiveness would be critically dependent upon spray pattern and droplet size (8:47).

Rating assigned: 3

<u>Effectiveness (Class C fires)</u>. It is assumed that the majority of electrical equipment on the station would be kept

in racks or other enclosed places. Again, the same rating scale used for class A fires will be used here.

CO2. CO2 is effective against electrical fires; it is not conductive (28:13-17).

Rating assigned: 4

N2. As in the class B fire situation, N2 might be about as effective as CO2. Again, however, due to lack of supporting data, it is subjectively judged slightly inferior to CO2.

Rating assigned: 3

Multipurpose Dry Chemical. On a weight basis, dry chemical is about twice as effective as CO2 on electrical fires (28:16-20).

Rating assigned: 5

High Expansion Foam. Foam is very effective when used in enclosed areas (40:1). No information on the conductivity of foam could be found; it is assumed that, even when deionized water is used to generate the foam, it could possibly transmit an electric current from the fire area to the user.

Rating assigned: 1

Halon 1301. Halon 1301 is extremely effective against electrical fires, on a par with dry chemicals (28:16-20).

Rating assigned: 5

Deionized Water. As discussed earlier, preliminary information indicates that deionized water may be an effective agent for use against electrical fires. Its ability to get to fires in hard-to-reach places (i.e., behind an instrument panel) might depend upon the droplet size used.

Rating assigned: 4

A summary of the effectiveness ratings against class A, class B, and class C fires is given in Table IV-1.

Table IV-1

Effectiveness Ratings (1-5) - Localized Fire Scenario

	CLASS A	CLASS B	CLASS C
CO2	3	4	4
N2	2	3	3
D CHEM	3	5	5
FOAM	4	2	1
H1301	3	5	5
H2O	4	3	4

Toxicity. A three-point scale will be used to indicate toxicity of extinguishing agents or their decomposition (pyrolysis) products. A "one" rating indicates that the agent or its pyrolysis products can be very hazardous to health. A "two" indicates a potentially toxic agent that is not particularly dangerous when used in quantities required for a small fire. A "three" indicates either an agent that is non-toxic or one that can be efficiently removed by the ECLSS.

<u>CO2</u>. Carbon dioxide is a toxic gas. A two percent concentration in air causes a 50 percent increase in speed and depth of breathing; a three percent concentration causes a 100 percent increase in the same (41:4). Concentrations around 9-10 percent or higher can cause unconsciousness or even death if breathed for more than a few minutes (41:5, 28:13-17). Discharge of a medium size (10 pound) CO2 extinguisher inside a 6000 cubic foot module would produce about 88 cubic feet of CO2 gas, roughly a 1.5 percent concentration. In addition, the ECLSS will remove excess CO2 from the module atmosphere.

Rating assigned: 3

<u>N2</u>. Extra N2 in air is not toxic.

Rating assigned: 3

<u>Multipurpose Dry Chemical</u>. Dry chemical agents are basically nontoxic. However, if they are discharged in large quantities, they could cause breathing difficulties or irritation of the air passage (28:13-27).

Rating assigned: 3

<u>High Expansion Foam</u>. Foam is nontoxic. In one documented experiment, dogs completely immersed in foam for 90 minutes showed no ill effects (18:165).

Rating assigned: 3

<u>Halon 1301</u>. Halon 1301, in its "neat" state, is mildly toxic. Tests have shown that a 30 minute exposure to

concentrations of 4.5 percent in air can produce dizziness and loss of coordination (21:38). The National Fire Protection Association recommends exposure of no more than one minute to concentrations of 7 percent or greater (21:38). The decomposition (pyrolysis) products of Halon 1301, including hydrogen fluoride (HF) and bromine (Br) are even more toxic; a concentration of either in excess of 50 parts per million is considered dangerous (28:13-24).

There is no question that Halon 1301 or its byproducts, in the concentrations listed above, can be dangerous. What is not known, however, is the effect of long-term exposure to <u>low levels</u> of these compounds. The discharge of a 5 lb portable Halon 1301 extinguisher inside a 6000 cubic foot module at 70 degrees F would produce approximately 13 cubic feet of gas, or a concentration of about 0.2 percent. Although the amount of pyrolysis products produced is a function of many variables (such as the nature and intensity of the fire), tests performed with Halon 1301 have shown that the concentration is generally well below the danger level (28:13-25, 21:42). These concentrations might be acceptable for very short duration missions. But, for the lengthy missions of station crews (assuming the ECLSS could not remove Halon 1301, HF, etc., from the atmosphere), they may pose a significant risk.

Rating assigned: 1

<u>Deionized Water</u>. Water is non-toxic.

Rating assigned: 3

A summary of the toxicity ratings for each alternative is given in Table IV-2.

Table IV-2

Toxicity Ratings - Localized Fire Scenario

	CO_2	N_2	D CHEM	FOAM	H13C1	H_2O
Toxicity (1= high, 3= low)	3	3	3	3	1	3

<u>Adverse Effects on Equipment</u>. A three-point rating scale will be used; a "one" rating indicates that the agent could have lasting adverse effects. A "two" denotes an agent that could have temporary effects, but can be effectively cleaned up or neutralized. A "three" indicates that the agent should have no adverse effects on equipment.

<u>CO_2</u>. CO_2 should not affect station equipment. Rating assigned: 3

<u>N_2</u>. N_2 should not affect station equipment. Rating assigned: 3

<u>Multipurpose Dry Chemical</u>. The use of dry chemicals could pose a definite problem, as the fine particles might jam mechanical equipment or interfere with the proper operation of delicate electrical components (relays, switches, etc.). The ECLSS particulate control will be able to eventually remove most of the particles, even though it may be temporarily

overloaded. However, it is conceivable that many particles will not be dislodged.

Rating assigned: 1

<u>High Expansion Foam</u>. Foam would probably have about the same effect as dry chemical on equipment. Much of it could possibly be wiped from surfaces, but it might be difficult to remove from enclosed places such as electronic cabinets.

Rating assigned: 1

<u>Halon 1301</u>. The main problem with Halon 1301 would be the corrosive properties of its pyrolysis products. Although the amounts of these products produced might not be great, they could have damaging effects on sensitive equipment. For example, hydrogen fluoride is capable of etching glass (19:5).

Rating assigned: 1

<u>Deionized Water</u>. As mentioned previously, deionized water is a poor conductor of electricity, so it should not cause electrical short circuits. It could cause some temporary problems similar to those that might be caused by dry chemicals and foam. However, the ECLSS humidity control should be able to effectively remove excess water from the atmosphere.

Rating assigned: 2

A summary of the adverse effects ratings for each alternative is given in Table IV-3.

Table IV-3

Adverse Effects Ratings - Localized Fire Scenario

	CO_2	N_2	D CHEM	FOAM	H1301	H_2O
Adverse Effects (1=major, 3=minor)	3	3	1	1	1	2

<u>Extinguisher Cost/Weight</u>. Although much information was available on general effectiveness of extinguishing agents, insufficient data could be found to allow comparison of all alternatives on a cost or weight basis. As a result, the MOEs of extinguisher cost and extinguisher weight are eliminated from further consideration.

<u>Technical Readiness</u>. A "yes/no" will be used as the indicator of technical readiness. A "yes" indicates that the agent is currently in use in a portable system aboard a U.S. spacecraft. A "no" indicates otherwise. Table IV-4 summarizes the technical readiness ratings.

Table IV-4

Technical Readiness Evaluation - Localized Fire Scenario

	CO_2	N_2	D CHEM	FOAM	H1301	H_2O
Technically Ready?	No	No	No	No	Yes	No

Large Fire/ Explosion Prevention Scenario

System Weight Required. This measure of effectiveness is shared by two objectives: Maximize effectiveness and minimize delivery cost. Obviously, it is desirable to minimize the weight required.

System weight is the sum of the weight of agent required to prevent a hydrogen explosion in a module and the weight of the storage container required for the agent. All other system components, such as plumbing and electrical circuitry, are assumed to be essentially identical for all agents.

A number of calculations are necessary to determine the required weight of each alternative agent. The following constants will be used:

P(AIR) (pressure of air in station) = 2116 lb/square ft

T (station temperature) = 530 degrees R (70 degrees F)

V (module volume) = 6000 cubic ft

R (universal gas constant) = 1545 ft-lb/lb-degree R

All gases will be assumed to be ideal gases.

Given % (X), which is the volume percentage of alternative agent X that is required in the module atmosphere to prevent a hydrogen explosion, the resulting partial pressure of X, P(X), can be found from the following relationship:

$$\frac{P(X)}{(P(AIR) + P(X))} * 100 = \%(X) \qquad (1)$$

The weight of alternative agent X that is required, W(X), is then:

$$W(X) = \frac{P(X)\ M(X)\ V}{R\ T} \qquad (2)$$

where M(X) is the molecular weight of alternative agent X.

$\underline{CO_2}$. If CO_2 is used to inert the atmosphere, the minimum volume percentage required is 57 percent (23:32). From equation (1), therefore, $P(CO_2)$ is 2815.2 lb/square ft (19.55 psi). CO_2 has a molecular weight of 44.01 lb, so, from equation (2), $W(CO_2)$ is 907.8 lb.

At 70 degrees F , liquefied CO_2 weighs 47.3 lb/cubic ft, so total storage volume required for 907.8 lb is 19.2 cubic feet (2). The required storage container would weigh approximately 17.8 lb per cubic foot of storage, resulting in container weight of 341.4 pounds (2).

Total system weight for CO_2 is therefore 1248.7 lb per module.

$\underline{N_2}$. The minimum volume percentage of N_2 required to inert a module is 71 percent (23:32). It follows that $P(N_2)$ is 5182.6 lb/cubic ft (35.99 psi). The molecular weight of N_2 is 28.01 lb, thus $W(N_2)$ is 1063.7 lb.

At 70 degrees F and 3000 psi, the density of gaseous N_2 is 14.77 lb/cubic ft; consequently, the amount of storage required is 72 cubic feet. The required storage vessel for N_2would weigh 25 lb/cubic ft of storage, or a total of 1800 lb (2).

Total system weight for N_2 is 2863.7 lb per module.

Halon 1301. The minimum volume percentage of Halon 1301 required to protect against a hydrogen explosion is 20 percent (23:32). P(H1301) is calculated to be 529.2 lb/cubic ft, or 3.68 psi. Since the molecular weight of Halon 1301 is 149 lb, W(H1301) is 577.8 lb.

At 70 degrees F, the density of liquid Halon 1301 is 98 lb/cubic ft, therefore, 5.89 cubic feet of storage are required (11:36). Using a container weight of 4.5 lb/cubic ft of storage capacity, the container would weigh a total of 26.5 lb (2).

The total weight of the Halon 1301 system would be 604 lb per module.

A summary of system weights for each alternative is given in Table IV-5.

Table IV-5

System Weight - Large Fire/Explosion Prevention Scenario

	CO_2	N_2	H1301
System Weight (lbs per module)	1248.7	2863.7	604

Module Pressure. This measure is obtained by adding the partial pressure required for agent X , which was obtained using equation (1), to module air pressure, which is 1 atmosphere (14.7 psi). Table IV-6 shows the module pressures resulting from the use of each alternative.

Table IV-6

Module Pressure - Large Fire/Explosion Prevention Scenario

	CO2	N2	H1301
Module Pressure (atmospheres)	2.33	3.45	1.25

Adverse Effects on Equipment. For this measure of effectiveness, the following three-point scale will be used: A "one" indicates potentially severe effects; a "two" indicates moderate effects; a "three" indicates that the agent should have no adverse effects on station equipment.

CO2. CO2 should not have any adverse effects.

Rating assigned: 3

N2. N2 should not have any adverse effects.

Rating assigned: 3

Halon 1301. In its neat state, Halon 1301 can cause some minor swelling of certain plastics and elastomers (37:94). This could be the case if the agent was discharged to prevent an explosion. If a fire was the reason for discharge, corrosive pyrolysis products could also be produced, as discussed previously.

Rating assigned: 1

Table IV-7 summarizes the adverse effects ratings.

Agent Cost. Agent requirements per module are: CO2, 907.8 lb; N2, 1063.7 lb (14,700 cubic ft); Halon 1301, 907.8 lb. To calculate cost, the following approximate figures were used: CO2, $.50/lb; N2, $1.00/ft^3; Halon 1301, $6.00/lb (25,27). Table IV-8 depicts the approximate agent cost per module.

Table IV-7

Adverse Effects - Large Fire/Explosion Prevention Scenario

	CO2	N2	H1301
Adverse Effects 1= high, 3= low	3	3	1

Table IV-8

Agent Cost - Large Fire/Explosion Prevention Scenario

	CO2	N2	H1301
Agent Cost ($/module)	454	14700	3465

Technical Readiness. A "yes/no" will be used as the indicator of technical readiness. A "yes" indicates that the agent is currently in use in a portable system aboard a U.S. spacecraft. A "no" indicates otherwise. Table IV-9 summarizes the technical readiness ratings.

Table IV-9

Technical Readiness Evaluation - Large Fire Scenario

	CO_2	N_2	H1301
Technically Ready ?	No	No	Yes

<u>Summary</u>

In this chapter, the performance of the alternatives for each scenario was analyzed with respect to the scenario's measures of effectiveness. The results will be utilized in the next chapter to determine the most promising alternative for each scenario.

V. Decision Making

Methodology

The methodology chosen for this step is Saaty's Analytical Hierarchy Process, or AHP, developed by Dr. Thomas Saaty of the University of Pennsylvania (31). It is a flexible methodology that is well-suited for use on problems in which the decision maker must use subjective opinion and intuition to arrive at a solution (31). The three steps involved in AHP are (31):

(1) Forming a hierarchy

(2) Making pairwise comparisons

(3) Synthesizing individual comparisons into overall priorities

To illustrate the use of this procedure, a brief conceptual example is provided by Crawford and Williams (6:12): Consider the problem of purchasing an automobile. The problem can be set up in a hierarchy, as in Figure V-1. The highest level, as shown, is the final selection of the automobile. The second level consists of automobile attributes, which may consist of status, cost, economy, and size. The lowest level consists of the automobile models considered (H,T,M,D,and C). The automobiles are ranked, using pairwise comparisons, according to each of the attributes (ratings are normalized to sum to one). The attributes are ranked according to their importance relative to the overall objective of selecting an automobile (ratings are normalized to sum to one). The synthesis step

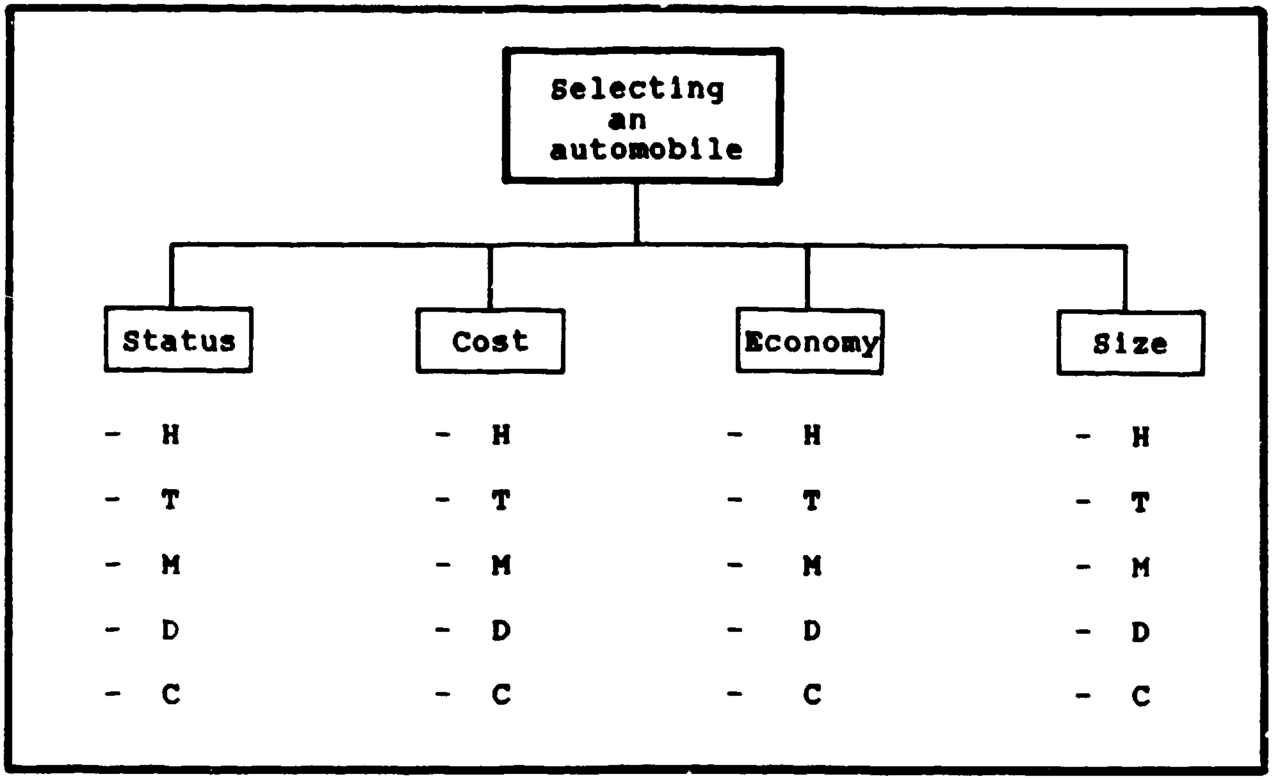

Figure V-1

Objective Hierarchy - Automobile Example

combines the ratings with respect to each attribute to obtain a final rating of each automobile with respect to the overall objective (again, ratings are normalized to sum to one). The decision maker would then choose the automobile with the highest rating.

For the sake of brevity, further discussion of the actual mechanics of AHP, including the pairwise comparisons and the synthesis, will be omitted here. However, for the interested reader, Appendix A contains more information on AHP as well as a summary of the individual pairwise comparisons conducted for this problem.

Solution

AHP can be a time-consuming process when dealing with numerous measures of effectiveness and alternatives. A computer and a good software package can be very helpful in this situation. For this study, the software "Expert Choice" by Decision Support Systems, Inc., was used to aid in the pairwise comparisons and to perform the synthesis. Tables V-1 and V-2 depict the hierarchies, as well as the relative priority (importance) of each MOE and of the alternatives with respect to each MOE.

For the localized fire scenario, shown in Table V-1, the decision maker's (author's) judgment determined that agent toxicity is the most important MOE, with a priority of 0.422, while technical readiness is the least important MOE, with a priority of 0.027. The differences in the three effectiveness ratings are a result of the perceived likelihood of each type of fire occurring on the station.

Underneath each MOE is the set of alternatives and the priority of each alternative with respect to that MOE. For example, under the EFF CL A (class A effectiveness) MOE, high expansion foam and deionized water have the highest ratings (0.208) while nitrogen has the lowest rating (0.105). These ratings were derived, using pairwise comparisons, from the results of the systems analysis in Chapter IV.

For the large fire/explosion prevention scenario, shown in Table V-2, the most important measure of effectiveness (according to the author's judgment) is MODPRESS (module pressure), which has a priority of 0.554, while AGENT $$ (agent cost) is least important, with a priority of 0.031.

Table V-1

Priorities - Localized Fire Scenario

'BEST' SYSTEM

	EFF CL A (0.074)	EFF CL B (0.115)	EFF CL C (0.115)	TOXICITY (0.422)	ADV EFF (0.247)	TECH RDY (0.027)
- CO_2	(0.159)	(0.183)	(0.184)	(0.194)	(0.341)	(0.071)
- N_2	(0.105)	(0.136)	(0.137)	(0.194)	(0.341)	(0.071)
- D CHEM	(0.159)	(0.227)	(0.225)	(0.194)	(0.049)	(0.071)
- FOAM	(0.208)	(0.091)	(0.045)	(0.194)	(0.049)	(0.071)
- H 1301	(0.159)	(0.227)	(0.225)	(0.032)	(0.049)	(0.643)
- H_2O	(0.208)	(0.136)	(0.184)	(0.194)	(0.171)	(0.071)

Table V-2

Priorities - Large Fire/ Explosion Prevention Scenario

'BEST' SYSTEM

	SYS WT (0.142)	MODPRESS (0.554)	ADV EFF (0.227)	AGENT $$ (0.031)	TECH RDY (0.045)
CO2	(0.299)	(0.281)	(0.467)	(0.743)	(0.091)
N2	(0.124)	(0.188)	(0.467)	(0.063)	(0.091)
H 1301	(0.577)	(0.531)	(0.067)	(0.194)	(0.818)

Overall priorities were synthesized using the priorities from Tables V-1 and V-2, and are shown in Tables V-3 and V-4. In the localized fire scenario, CO2, with an overall priority of 0.222, won by a narrow margin over N2, which had a priority of 0.20[illegible]. A fairly uniform decrease between each successively lower alternative was observed. In the large fire/ explosion prevention scenario, Halon 1301 had a substantial, but not overwhelming, margin over CO2, 0.434 to 0.332, with about the same margin between CO2 and N2.

Table V-3

Overall Priorities - Localized Fire Scenario

CO2	0.222	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
N2	0.207	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
H2O	0.178	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
D CHEM	0.159	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
FOAM	0.127	XXXXXXXXXXXXXXXXXXXXXXXXXX
H1301	0.107	XXXXXXXXXXXXXXXXXXXXX
	1.000	

Table V-4

Overall Priorities - Large Fire/Explosion Prevention Scenario

H1301	0.434	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
CO2	0.332	XXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXXX
N2	0.234	XXXXXXXXXXXXXXXXXXXXXXX
	1.000	

Sensitivity Analysis

It is important to note that the results from AHP are largely a function of the individual decision maker's preferences, especially when subjectivity must be used in making pairwise comparisons. Sensitivity analysis can help to reduce uncertainty by showing exactly how "sensitive" the results of AHP are to either a change of decision maker or a change in the existing decision maker's priorities. In this problem, the majority of the subjectivity occurred when determining the relative importance of the measures of effectiveness. Therefore, sensitivity analysis will be performed on the MOEs.

Explanation of Sensitivity Analysis Graphs. "Expert Choice" was used to construct the sensitivity analysis graphs which appear in Figures V-2 and B-1 through B-12. In each case, the vertical axis depicts overall priority of the alternative, while the horizontal axis represents priority of the MOE relative to the other MOEs. The dashed vertical line (or priority index) performs two functions: first, its intersection with the horizontal axis indicates the current priority of the particular MOE; second, the vertical distance to its intersection with the line representing each alternative is the current overall priority of that alternative. For example, in Figure V-3, the priority index intersects the horizontal axis at a value of 0.074, which is the current priority of the "EFF CL A" measure of effectiveness. The same line intersects the CO2 line at a vertical axis value of 0.222, which is the overall priority of CO2 for the localized fire scenario.

By shifting the priority index back and forth along the horizontal axis, one can observe how changes in the priority of the MOE might affect the relative overall priorities of the alternatives. As shown in Figure V-2, CO2 would retain the highest priority in the localized fire scenario unless the priority for the "EFF CL A" measure of effectiveness increased to approximately 0.5 or higher with respect to the other MOEs. At that point, the "best" overall alternative would become H2O.

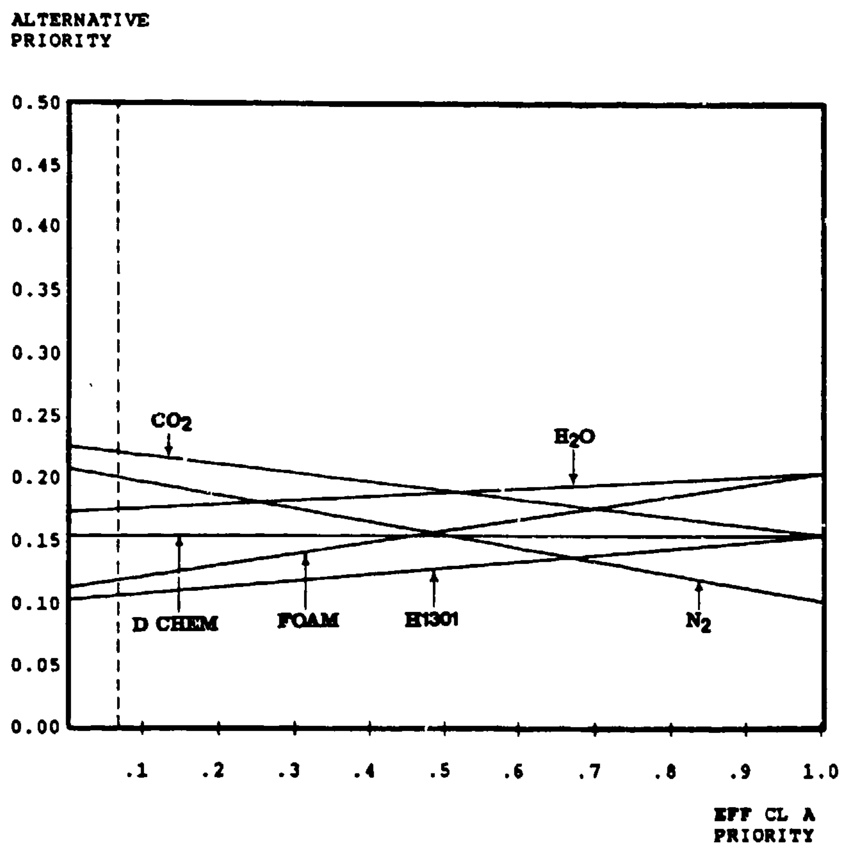

Figure V-2

Sensitivity of Solution to Changes in Priority of Class A Effectiveness - Localized Fire Scenario

CO_2 is dominant over a wide range of priorities for the other MOEs as well; this is graphically depicted in Appendix B. For the EFF CL B and EFF CL C measures of effectiveness, the priority of either would have to increase to over 0.6 (from the current priority of 0.115) to cause an alternative other than CO_2 to become the preferred alternative. With regard to the TOXICITY MOE, CO_2 is dominant until the priority increases to 1.0 (from its current value of 0.422), at which time it is tied with a number of the other alternatives. With regard to the ADV EFF measure of effectiveness, the range of dominance of CO_2 is between priorities of 0.05 and 1.0. CO_2 has the its smallest range of dominance with respect to the TECH RDY MOE. There, if the priority of TECH RDY increases to 0.18 (from its current 0.027), Halon 1301 would be the preferred agent.

Sensitivity analysis graphs for the large fire/explosion prevention scenario are also located in Appendix B. Halon 1301 is shown to be completely dominant with respect to all possible priorities of the SYS WT and TECH RDY measures of effectiveness. An increase of at least 0.15 in the priority of either the AGENT $$ or the ADV EFF MOEs would result in CO_2 becoming the highest rated alternative, due to its superior performance over Halon 1301 in these two areas. With regard to the MODPRESS measure of effectiveness, if the priority of this MOE were to decrease to approximately 0.25 (from its current 0.554), CO_2 would become dominant over Halon 1301, since Halon 1301 had the best module pressure rating.

Overall, the sensitivity analysis seems to indicate that the solution for each scenario is fairly robust; that is, many decision makers would probably arrive at the same solutions given in this study. This can be said because of the generally large changes in MOE priorities that would have to be made for another of the alternatives to become the preferred solution.

VI. Conclusions

The purpose of this study was to determine which of several existing fire extinguishing agents could best be adapted for use aboard the manned space station. Hall's methodology, which is a systems engineering approach, was used to establish the framework upon which the solution to the problem would be based. After the definition of specific objectives, measures of effectiveness were developed to allow the alternatives to be compared to one another on the basis of performance. Each individual alternative was assigned a score for each measure of effectiveness. Saaty's Analytical Hierarchy Process was then used to determine an overall score for each alternative.

For the localized fire scenario, carbon dioxide would be the best agent to use in hand-held extinguishers. Even though it is not the best in all categories of performance, it is generally superior to foam, water, and nitrogen in effectiveness against most types of fires; it is vastly superior to Halon 1301 in toxicity and to dry chemicals in terms of adverse effects on equipment.

For the large fire/explosion prevention scenario, Halon 1301 was found to be superior to the other alternatives in the most important performance measures (system weight and module pressure). Although its potential adverse effects, especially in regard to a large fire, are more severe than the other alternatives, it is likely that these adverse effects would not be significant when compared to the fire damage itself. Of course, the results depend heavily on how the decision maker weights the individual MOEs, but sensitivity analysis showed that the results obtained in this study would be valid over a wide range of weights for each measure of effectiveness.

As mentioned previously, the purpose of this study was to determine the best interim method to extinguish potential fires on the space station. It is important that further research be conducted in space, either to verify the performance of agents considered in this study, or to test new ones. It is understood that some fire and extinguisher research is planned for a future Spacelab mission, however, it is probable that detailed research will not be accomplished until the space station is in place. Hopefully, a fire will never occur on the station, but NASA must be prepared.

Appendix A: The Analytical Hierarchy Process

In this section, the basics of AHP will be discussed and an example problem will be worked. Finally, a summary of all pairwise comparisons made for this study will be included. Except as noted, the methodology used throughout the section was drawn from the book Decision Making For Leaders by Thomas L. Saaty (38:76-90).

AHP Basics

As mentioned in Chapter V, AHP involves three steps:

(1) Forming a hierarchy

(2) Making pairwise comparisons and computing priorities and weights

(3) Synthesizing individual comparisons into overall priorities

As an example, an AHP hierarchy will be generated for the large fire/explosion prevention scenario. This hierarchy, shown in Figure A-1, is based upon the hierarchy of Figure II-5, but consists only of the overall objective, the measures of effectiveness, and the alternatives. The intermediate objectives of Figure II-5 are eliminated, as they do not enter into the AHP calculations.

To determine relative importance of the elements at each level of the hierarchy, pairwise comparisons must be made. In this example, system weight, module pressure, and the other MOEs are compared against one another to determine their relative importance to the decision maker. Then, the relative performances of the alternatives with respect to system weight, module

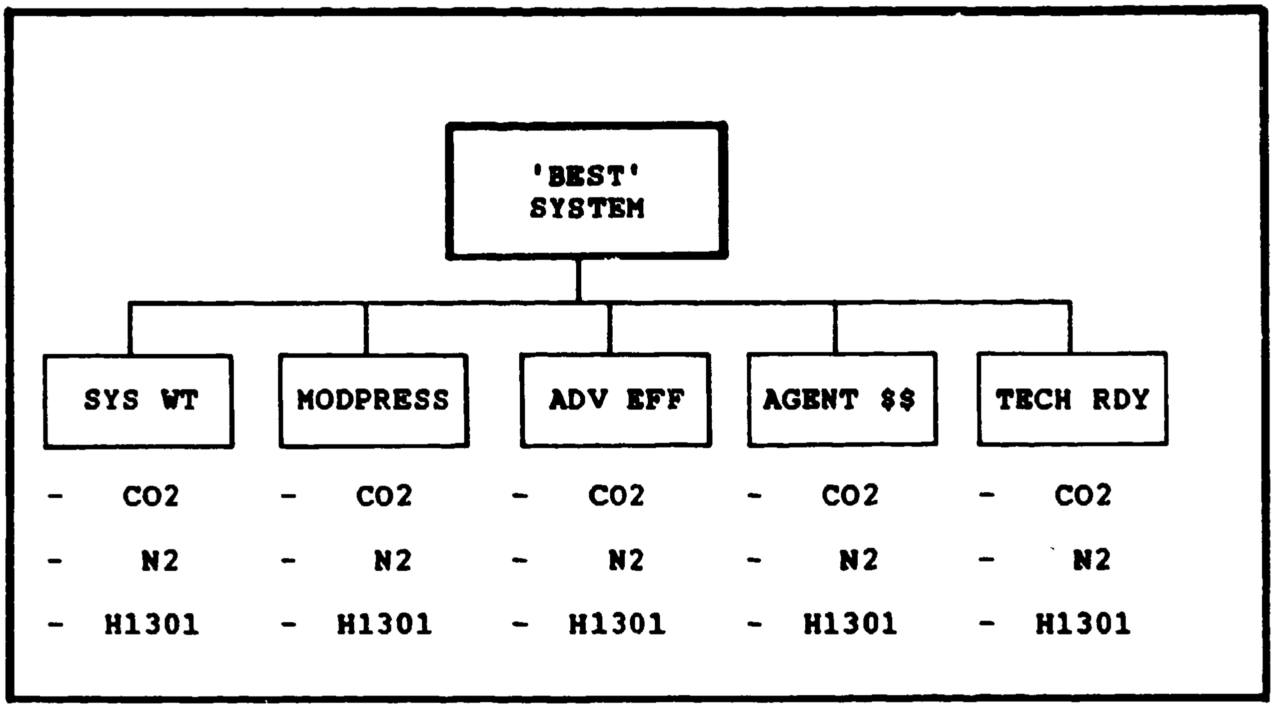

Figure A-1

AHP Hierarchy - Large Fire/ Explosion Prevention Scenario

pressure, and the other measures of effectiveness are assessed.

The pairwise comparisons between the measures of effectiveness are necessarily subjective and reflect the values of the decision maker. The AHP comparison scale depicted in Figure A-2 was used as an aid in making the pairwise comparisons between the MOEs in each scenario. Pairwise comparisons between the alternatives for each MOE were, in general, made directly from the ratings assigned in Chapter IV (exceptions will be discussed later).

To illustrate this concept, the alternatives for the large fire scenario will be evaluated with respect to the "module pressure" measure of effectiveness. Table A-1 depicts the comparison matrix.

INTENSITY OF IMPORTANCE	DEFINITION	EXPLANATION
1	Equal importance	Two activities contribute equally to the objective.
3	Weak importance of one over another	Experience and judgment slightly favor one activity over the other.
5	Essential or strong importance	Experience and judgment strongly favor one activity over another.
7	Very strong or demonstrated performance	An activity is favored very strongly over another; its dominance demonstrated in practice.
9	Absolute importance	The evidence favoring one activity over another is of the highest possible order of affirmation.
2,4,6,8	Intermediate values	When compromise is needed.

Figure A-2

AHP Comparison Scale (31)

The comparisons for the matrix were made on the basis of the figures for module pressure derived in Chapter IV. For example, the pressure when Halon 1301 is used is 1.85 times more favorable than CO2 and 2.75 times more favorable than N2. Therefore, the number 1.85 is entered on the H1301 row in the CO2 column and 2.75 is entered on the same row in the N2 column; a 1.0 is entered automatically when an alternative is compared

Table A-1

Alternatives Comparison Matrix
With Respect to Module Pressure
(Large Fire/Explosion Prevention Scenario)

	CO2	N2	H1301
CO2	1.0	1.5	0.54
N2	0.67	1.0	0.36
H1301	1.85	2.75	1.0

to itself. It follows that, in the CO2 row, in the H1301 column, the required entry is 1/1.85 (0.54), and so forth.

To determine the relative priorities of the alternatives with respect to module pressure, the geometric mean for each row of the matrix must be calculated (6:6). These means are placed in a column vector and then normalized to sum to one to give the priorities. In this instance, since each row has three elements, the geometric mean is simply the cube root of the product of the row's elements. The geometric means of the rows of the above matrix are 0.9322, 0.6225, and 1.720 for rows 1,2, and 3, respectively. After normalizing, the following column vector, which is the priority vector for the module pressure MOE, is the result:

$$\begin{array}{r} \text{CO2} \\ \text{N2} \\ \text{H1301} \end{array} \begin{bmatrix} 0.28 \\ 0.19 \\ 0.53 \end{bmatrix}$$

Priority vectors for the alternatives with respect to all other measures of effectiveness are computed in the same manner. The priority vectors are then placed into a matrix, as shown in Table A-2.

Table A-2

Alternatives Priority Matrix
Large Fire/Explosion Prevention Scenario

	SYSTEM WEIGHT	MODULE PRESSURE	ADVERSE EFFECTS	AGENT COST	TECH READY
CO2	0.30	0.28	0.47	0.74	0.09
N2	0.12	0.19	0.47	0.06	0.09
H1301	0.58	0.53	0.06	0.20	0.82

For the large fire/explosion prevention scenario, pairwise comparisons of the measures of effectiveness with respect to each other result in the priority vector shown in Table A-3.

Table A-3

MOE Priority Vector - Large Fire/Explosion Prevention Scenario

$$\begin{array}{r} \text{SYSTEM WEIGHT} \\ \text{MODULE PRESSURE} \\ \text{ADVERSE EFFECTS} \\ \text{AGENT COST} \\ \text{TECH READINESS} \end{array} \begin{bmatrix} 0.14 \\ 0.55 \\ 0.23 \\ 0.03 \\ 0.05 \end{bmatrix}$$

Finally, the alternatives priority matrix and the MOE priority vector are multiplied together, yielding the overall priority vector for the large fire scenario, depicted in Table A-4. The numbers are slightly different than the ones presented in Chapter V due to round-off.

Table A-4

Overall Priorities - Large Fire/Explosion Prevention Scenario

CO2	0.24
N2	0.33
H1301	0.43

<u>Inconsistency Index</u>. In order to insure the highest possible validity of the AHP process, it is important that the judgments made by the decision maker are consistent. For instance, if A is rated twice as high as B, and B is rated twice as high as C, then, to be consistent, A should be rated four times higher than C. For a discussion of the computation of the inconsistency index, the interested reader may refer to Saaty. For this study, "Expert Choice" computed inconsistency indices for each comparison matrix and for the overall problem. An inconsistency index of less than 0.1 is considered acceptable; the largest inconsistency index for either scenario in this study was 0.05.

Summary of Pairwise Comparisons

The remainder of this appendix is devoted to the presentation of each pairwise comparison which was made in the study. As mentioned previously, pairwise comparisons between measures of effectiveness were made using the AHP Comparison Scale. For comparisons between alternatives, relative ratings from the analysis in Chapter IV were entered directly into the comparison matrices, in most cases. However, in some instances when three-point rating scales were used, such as in the measurement of toxicity, it was felt that the alternatives that received the highest rating were more than three times better than the alternatives receiving the lowest rating. As a result, some subjectivity entered into these comparisons.

Table A-5

MOE Comparison Matrix - Localized Fire Scenario

	EFF CL A	EFF CL B	EFF CL C	TOXI-CITY	ADV EFF	TECH RDY
EFF CL A	1.0	0.5	0.5	0.2	0.25	5.0
EFF CL B	2.0	1.0	1.0	0.25	0.33	6.0
EFF CL C	2.0	1.0	1.0	0.25	0.33	6.0
TOXICITY	5.0	4.0	4.0	1.0	3.0	8.0
ADV EFF	4.0	3.0	3.0	0.33	1.0	7.0
TECH RDY	0.2	0.17	0.17	0.12	0.14	1.0

Table A-6

Alternatives Comparison Matrix With Respect to Class A Effectiveness Localized Fire Scenario

	CO_2	N_2	D CHEM	HE FOAM	H1301	H_2O
CO_2	1.0	1.5	1.0	0.77	1.0	0.77
N_2	0.67	1.0	0.67	0.5	0.67	0.5
D CHEM	1.0	0.67	1.0	0.77	1.0	0.77
HE FOAM	1.3	2.0	1.3	1.0	1.3	1.0
H1301	1.0	1.5	1.0	0.77	1.0	0.77
H_2O	1.3	2.0	1.3	1.0	1.3	1.0

Table A-7

Alternatives Comparison Matrix
With Respect to Class B Effectiveness
Localized Fire Scenario

	CO2	N2	D CHEM	HE FOAM	H1301	H20
CO2	1.0	1.3	0.83	2.0	0.83	1.3
N2	0.77	1.0	0.59	1.5	0.59	1.0
D CHEM	1.2	1.7	1.0	2.5	1.0	1.7
HE FOAM	0.5	0.67	0.4	1.0	0.4	0.67
H1301	1.2	1.7	1.0	2.5	1.0	1.7
H20	0.77	1.0	0.59	1.5	0.59	1.0

Table A-8

Alternatives Comparison Matrix
With Respect to Class C Effectiveness
Localized Fire Scenario

	CO2	N2	D CHEM	HE FOAM	H1301	H20
CO2	1.0	1.3	0.83	4.0	0.83	1.0
N2	0.77	1.0	0.59	3.0	0.59	0.77
D CHEM	1.2	1.7	1.0	5.0	1.0	1.2
HE FOAM	0.25	0.33	0.2	1.0	0.2	0.25
H1301	1.2	1.7	1.0	0.2	1.0	1.2
H20	1.0	1.3	0.83	4.0	0.83	1.0

Table A-9
Alternatives Comparison Matrix
With Respect to Toxicity
Localized Fire Scenario

	CO2	N2	D CHEM	HE FOAM	H1301	H2O
CO2	1.0	1.0	1.0	1.0	6.0	1.0
N2	1.0	1.0	1.0	1.0	6.0	1.0
D CHEM	1.0	1.0	1.0	1.0	6.0	1.0
HE FOAM	1.0	1.0	1.0	1.0	6.0	1.0
H1301	0.17	0.17	0.17	0.17	1.0	0.17
H2O	1.0	1.0	1.0	1.0	6.0	1.0

Table A-10

Alternatives Comparison Matrix
With Respect to Adverse Effects
Localized Fire Scenario

	CO2	N2	D CHEM	HE FOAM	H1301	H2O
CO2	1.0	1.0	7.0	7.0	7.0	2.0
N2	1.0	1.0	7.0	7.0	7.0	2.0
D CHEM	0.14	0.14	1.0	1.0	1.0	0.29
HE FOAM	0.14	0.14	1.0	1.0	1.0	0.29
H1301	0.14	0.14	1.0	1.0	1.0	0.29
H2O	0.5	0.5	3.5	3.5	3.5	1.0

Table A-11

Alternatives Comparison Matrix
With Respect to Technical Readiness
Localized Fire Scenario

	CO2	N2	D CHEM	HE FOAM	H1301	H2O
CO2	1.0	1.0	1.0	1.0	0.11	1.0
N2	1.0	1.0	1.0	1.0	0.11	1.0
D CHEM	1.0	1.0	1.0	1.0	0.11	1.0
HE FOAM	1.0	1.0	1.0	1.0	0.11	1.0
H1301	9.0	9.0	9.0	9.0	1.0	9.0
H2O	1.0	1.0	1.0	1.0	0.11	1.0

Table A-12

MOE Comparison Matrix
Large Fire/Explosion Prevention Scenario

	SYS WT	MOD PRESS	ADV EFF	AGENT $$	TECH RDY
SYS WT	1.0	0.17	0.5	6.0	5.0
MOD PRESS	6.0	1.0	4.0	9.0	8.0
ADV EFF	2.0	0.25	1.0	8.0	7.0
AGENT $$	0.17	0.11	0.12	1.0	0.5
TECH RDY	0.2	0.12	0.14	2.0	1.0

Table A-13

Alternatives Comparison Matrix
With Respect to System Weight
Large Fire/Explosion Prevention Scenario

	CO2	N2	H1301
CO2	1.0	2.5	0.5
N2	0.4	1.0	0.22
H1301	2.0	4.5	1.0

Table A-14

Alternatives Comparison Matrix
With Respect to Module Pressure
Large Fire/Explosion Prevention Scenario

	CO2	N2	H1301
CO2	1.0	1.5	0.53
N2	0.67	1.0	0.36
H1301	1.9	2.8	1.0

Table A-15

Alternatives Comparison Matrix
With Respect to Adverse Effects
Large Fire/Explosion Prevention Scenario

	CO2	N2	H1301
CO2	1.0	1.0	7.0
N2	1.0	1.0	7.0
H1301	0.14	0.14	1.0

Table A-16

Alternatives Comparison Matrix
With Respect to Agent Cost
Large Fire/Explosion Prevention Scenario

	CO2	N2	H1301
CO2	1.0	9.0	5.0
N2	0.11	1.0	0.25
H1301	0.2	4.0	1.0

Table A-17

Alternatives Comparison Matrix
With Respect to Technical Readiness
Large Fire/Explosion Prevention Scenario

	CO2	N2	H1301
CO2	1.0	1.0	0.11
N2	1.0	1.0	0.11
H1301	9.0	9.0	1.0

Appendix B: <u>Sensitivity Analysis Graphs</u>

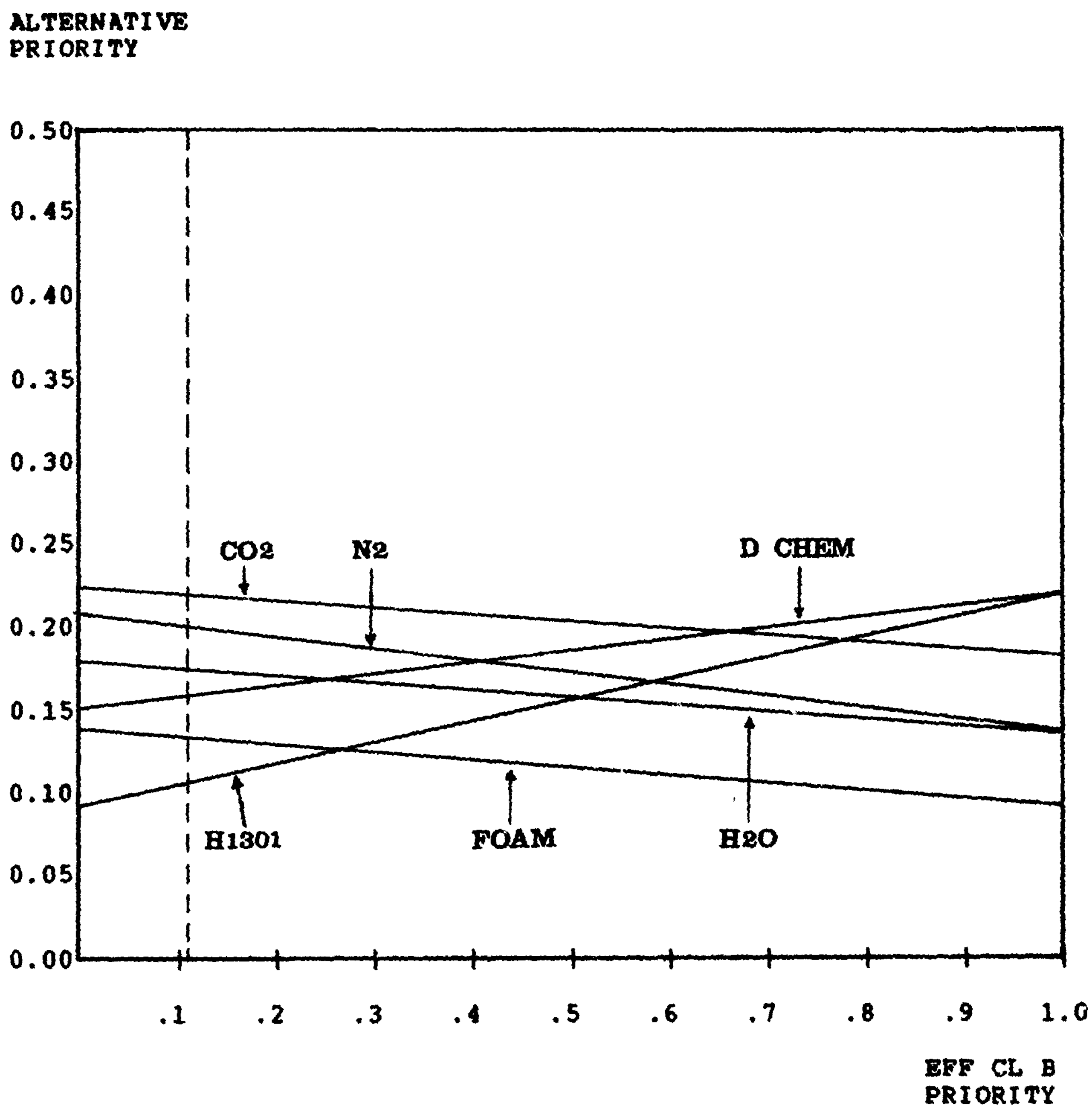

Figure B-1

Sensitivity of Alternatives' Priorities
to Priority of the Class B Effectiveness MOE
Localized Fire Scenario

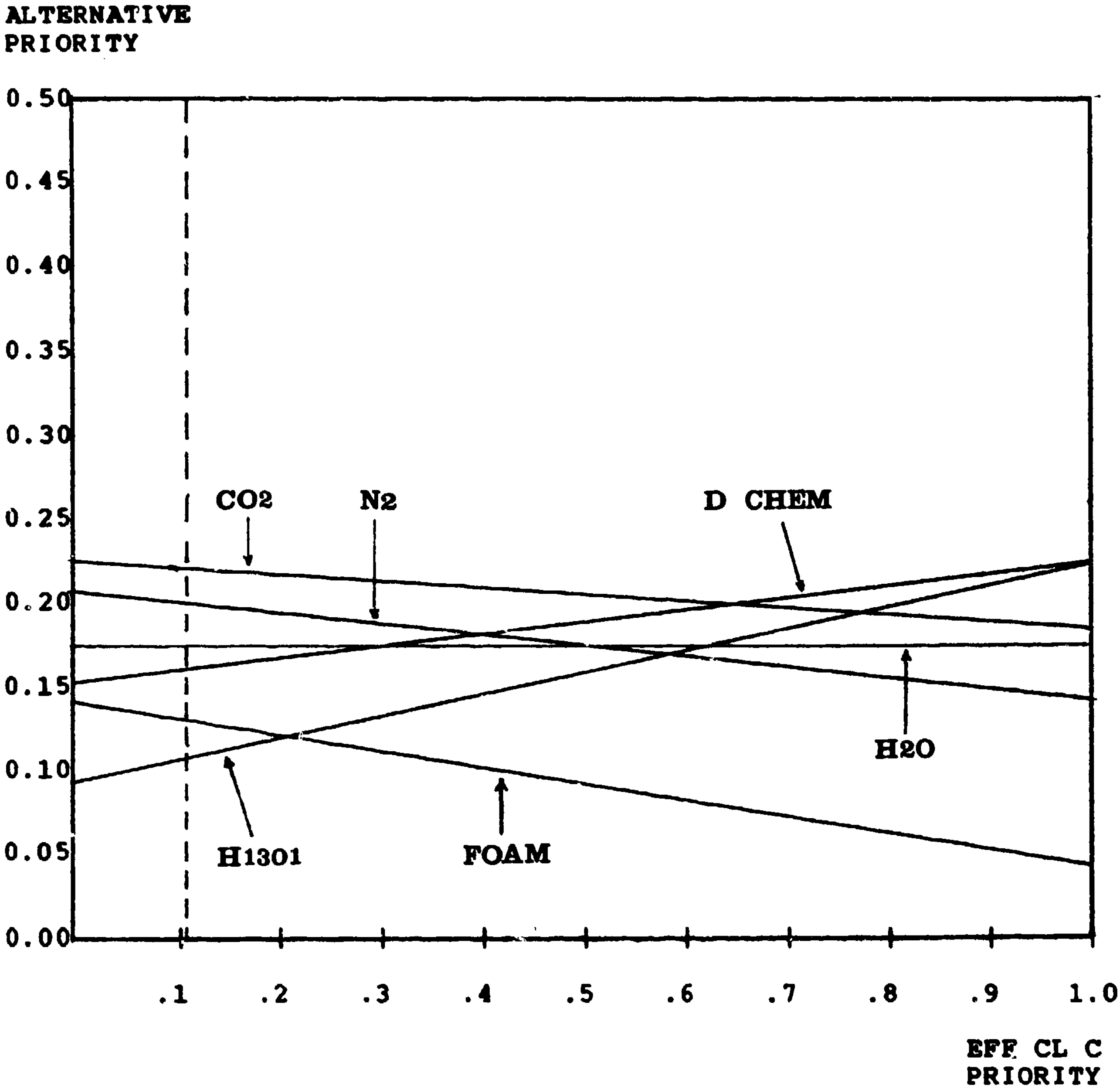

Figure B-2

Sensitivity of Alternatives' Priorities
to Priority of the Class C Effectiveness MOE
Localized Fire Scenario

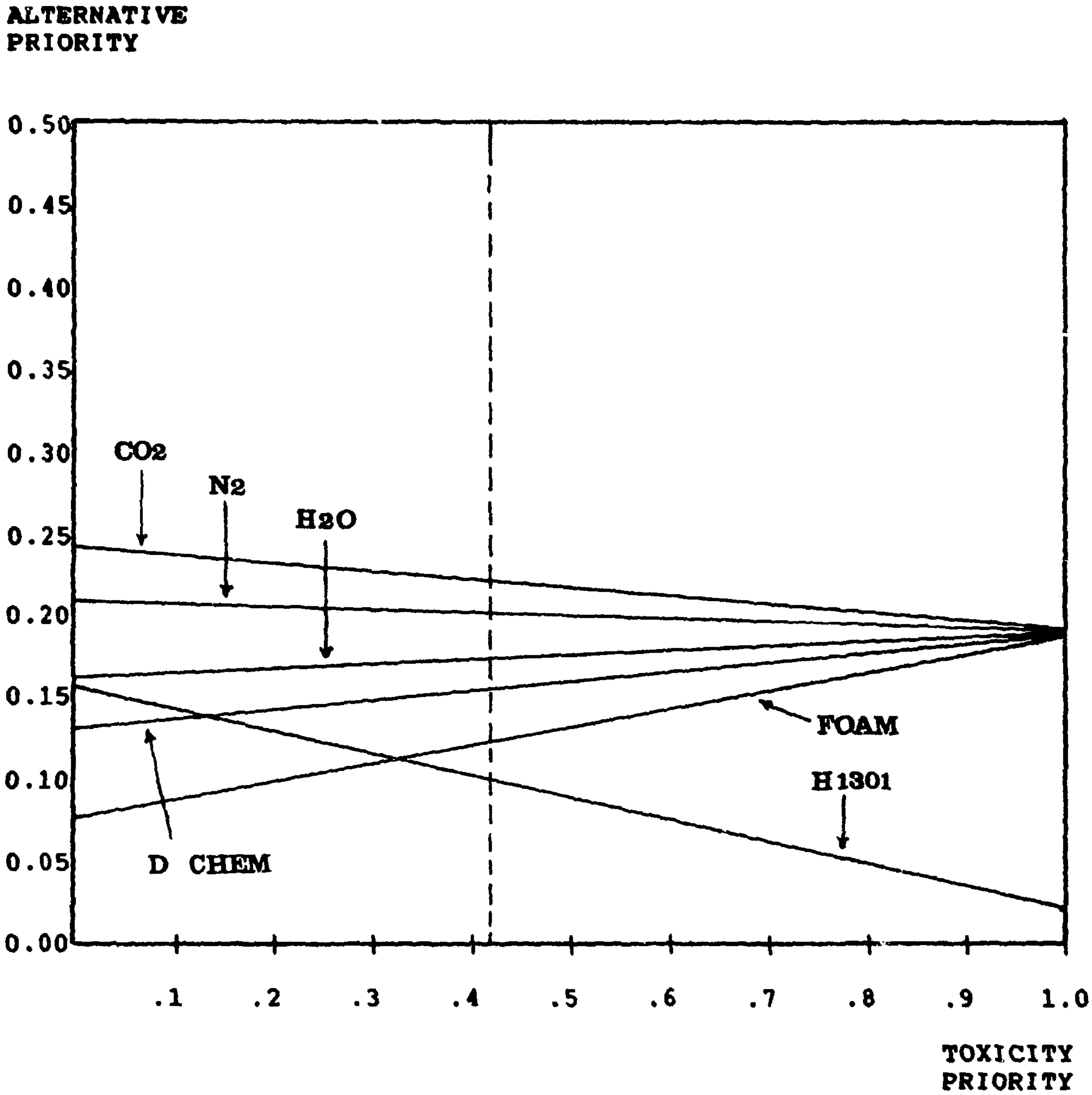

Figure B-3

Sensitivity of Alternatives' Priorities
to Priority of the Toxicity MOE
Localized Fire Scenario

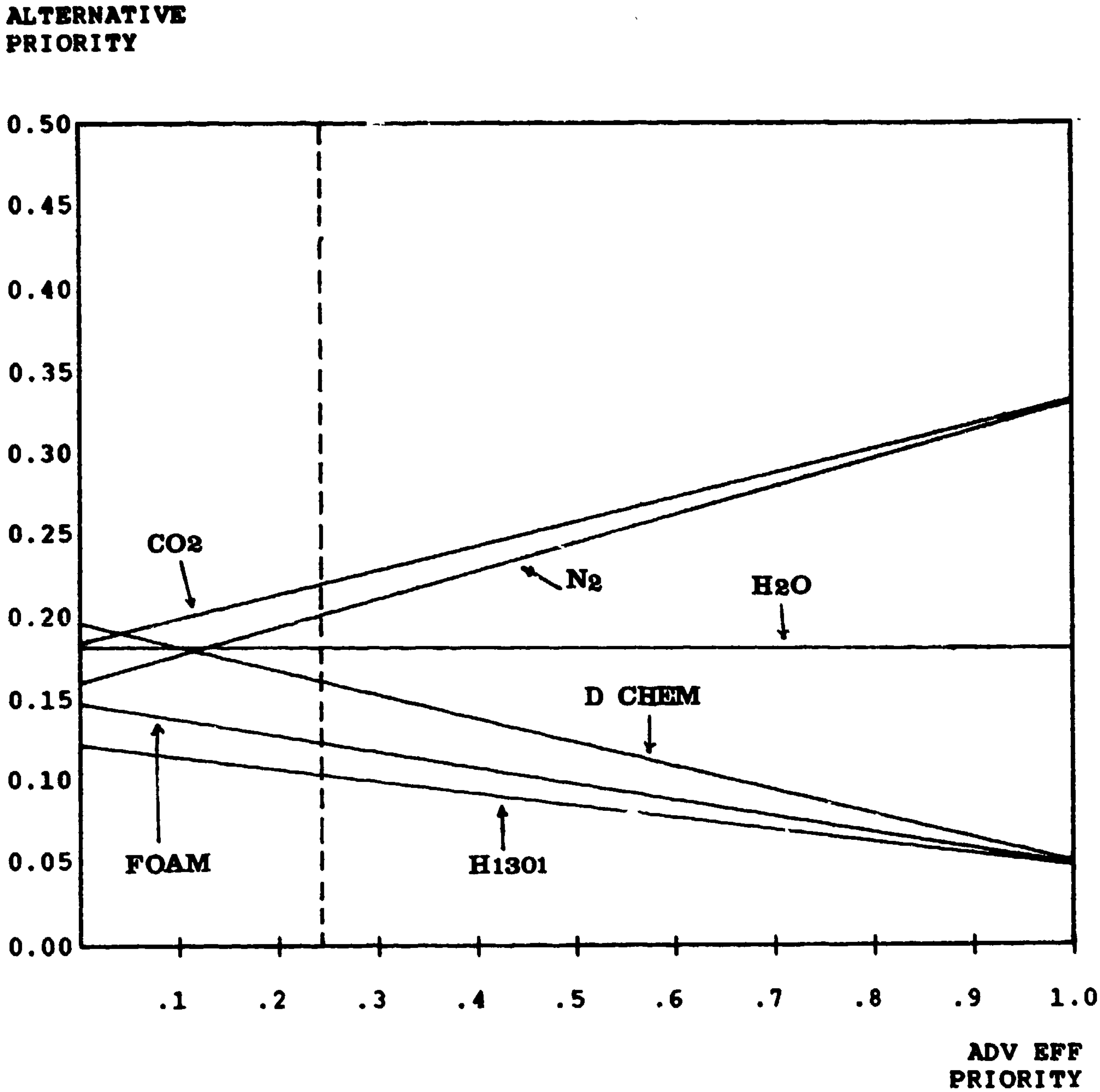

Figure B-4

Sensitivity of Alternatives' Priorities
to Priority of the Adverse Effects MOE
Localized Fire Scenario

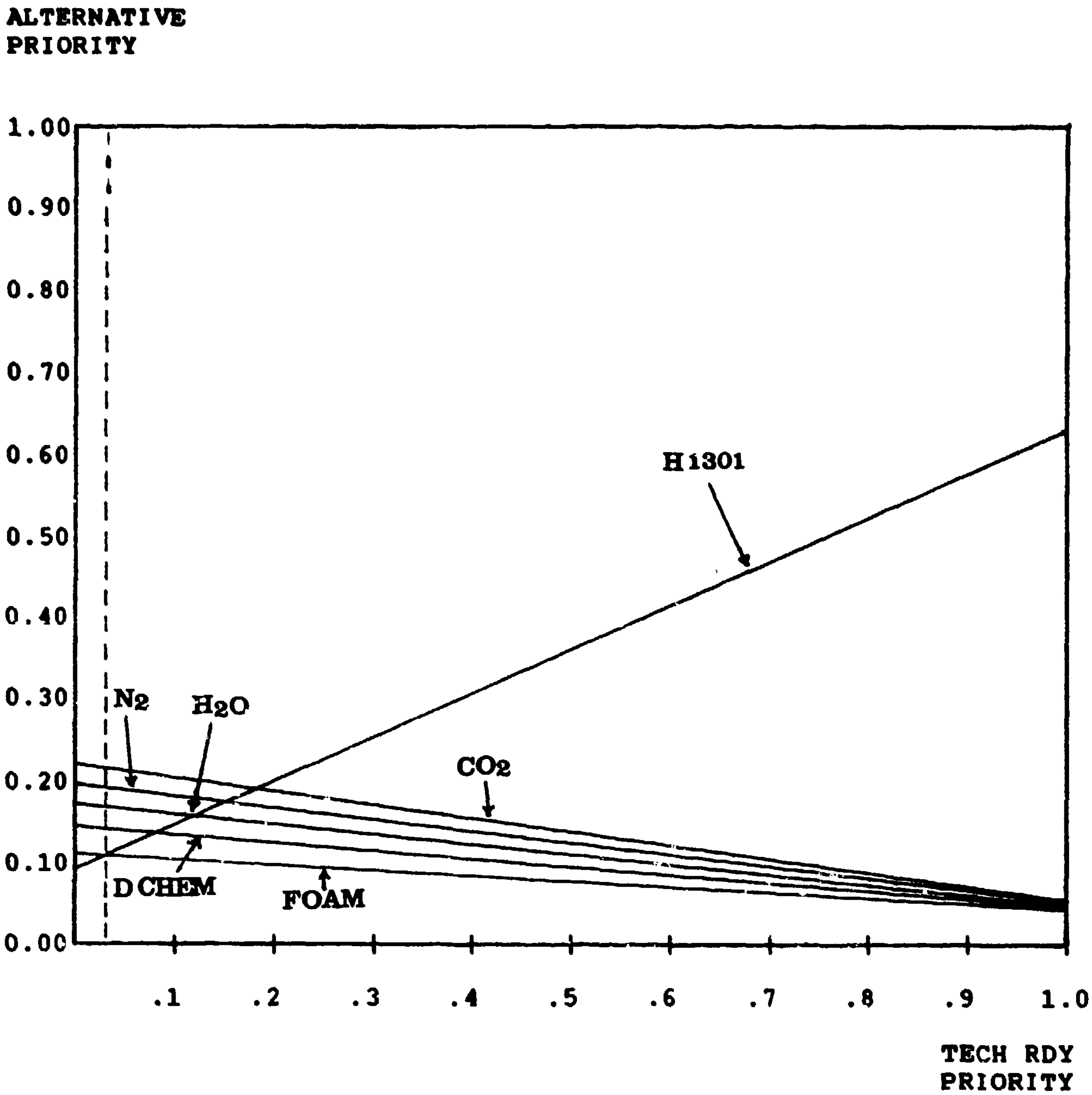

Figure B-5

Sensitivity of Alternatives' Priorities
to Priority of the Technical Readiness MOE
Localized Fire Scenario

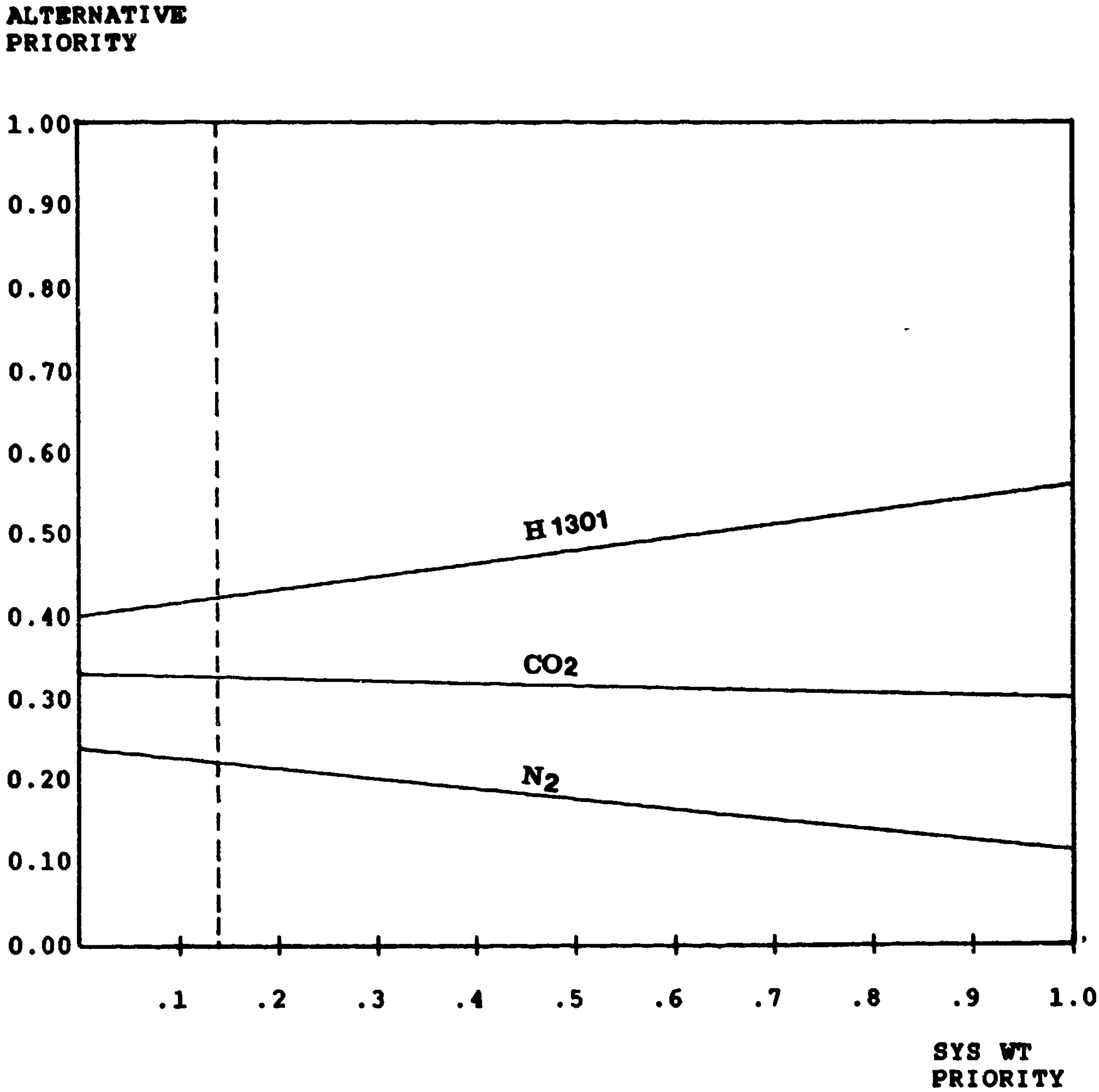

Figure B-6

Sensitivity of Alternatives' Priorities
to Priority of the System Weight MOE
Large Fire/Explosion Prevention Scenario

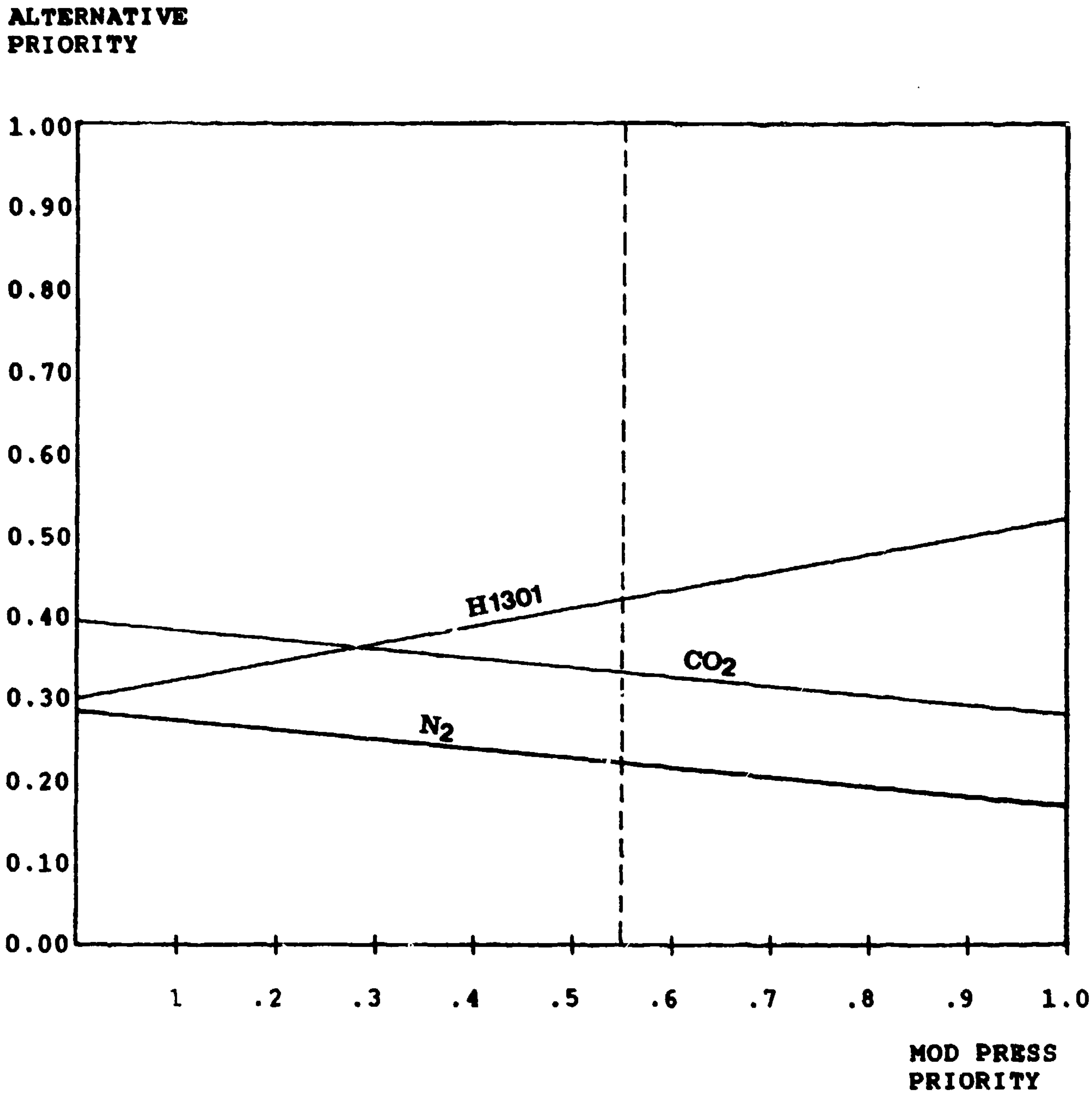

Figure B-7

Sensitivity of Alternatives' Priorities
to Priority of the Module Pressure MOE
Large Fire/Explosion Prevention Scenario

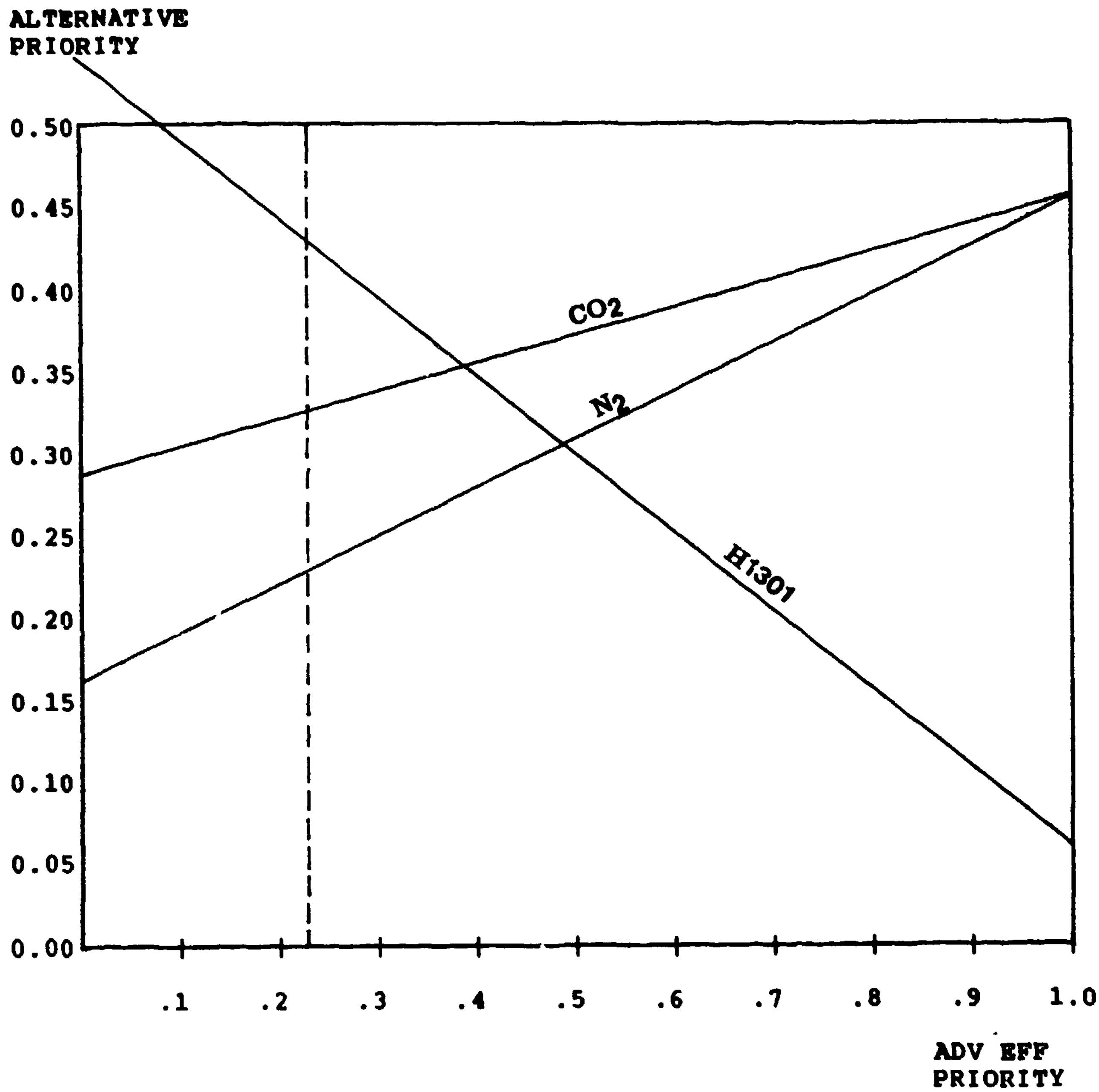

Figure B-8

Sensitivity of Alternatives' Priorities
to Priority of the Adverse Effects MOE
Large Fire/Explosion Prevention Scenario

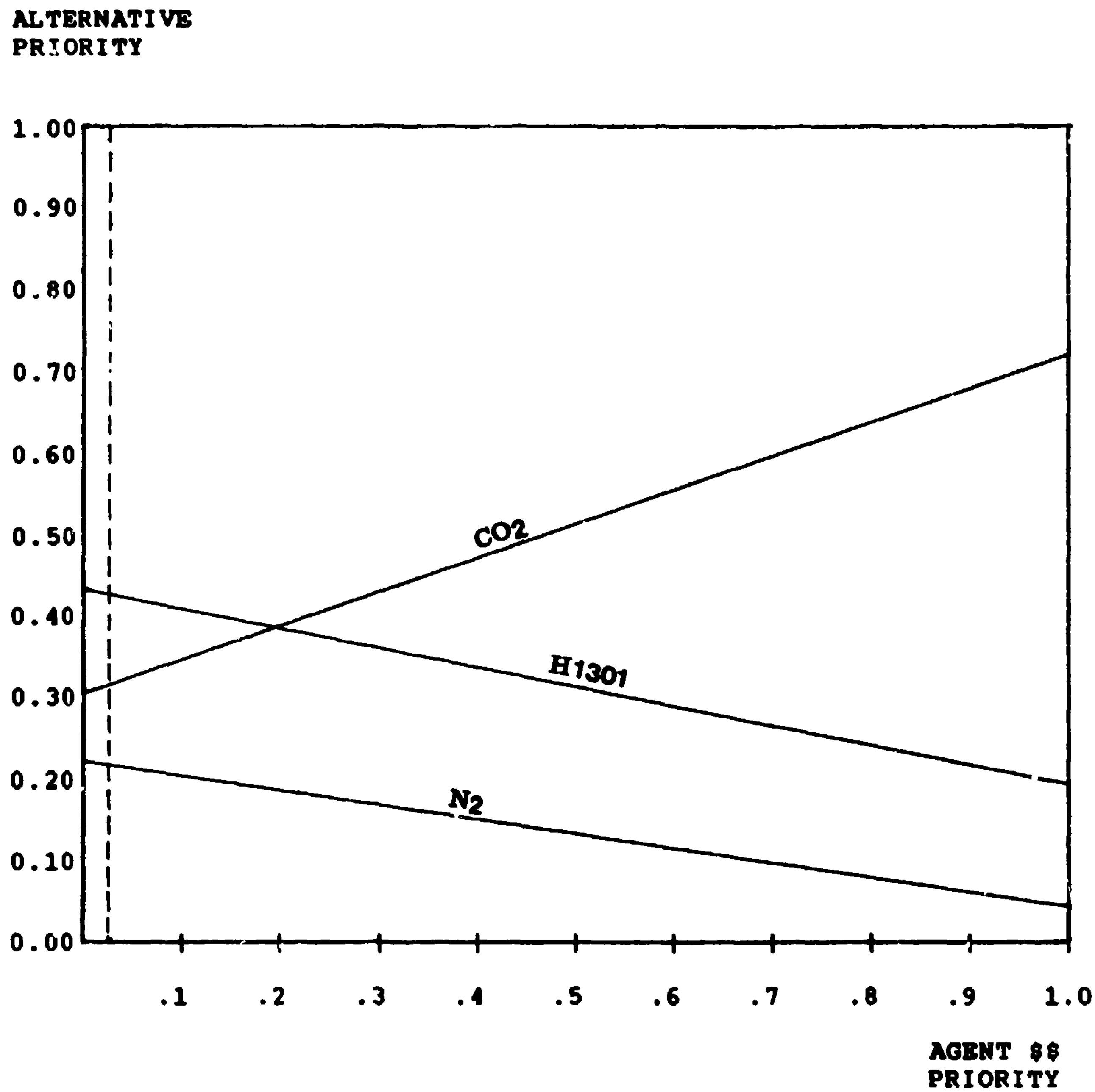

Figure B-9

Sensitivity of Alternatives' Priorities
to Priority of the Agent Cost MOE
Large Fire/Explosion Prevention Scenario

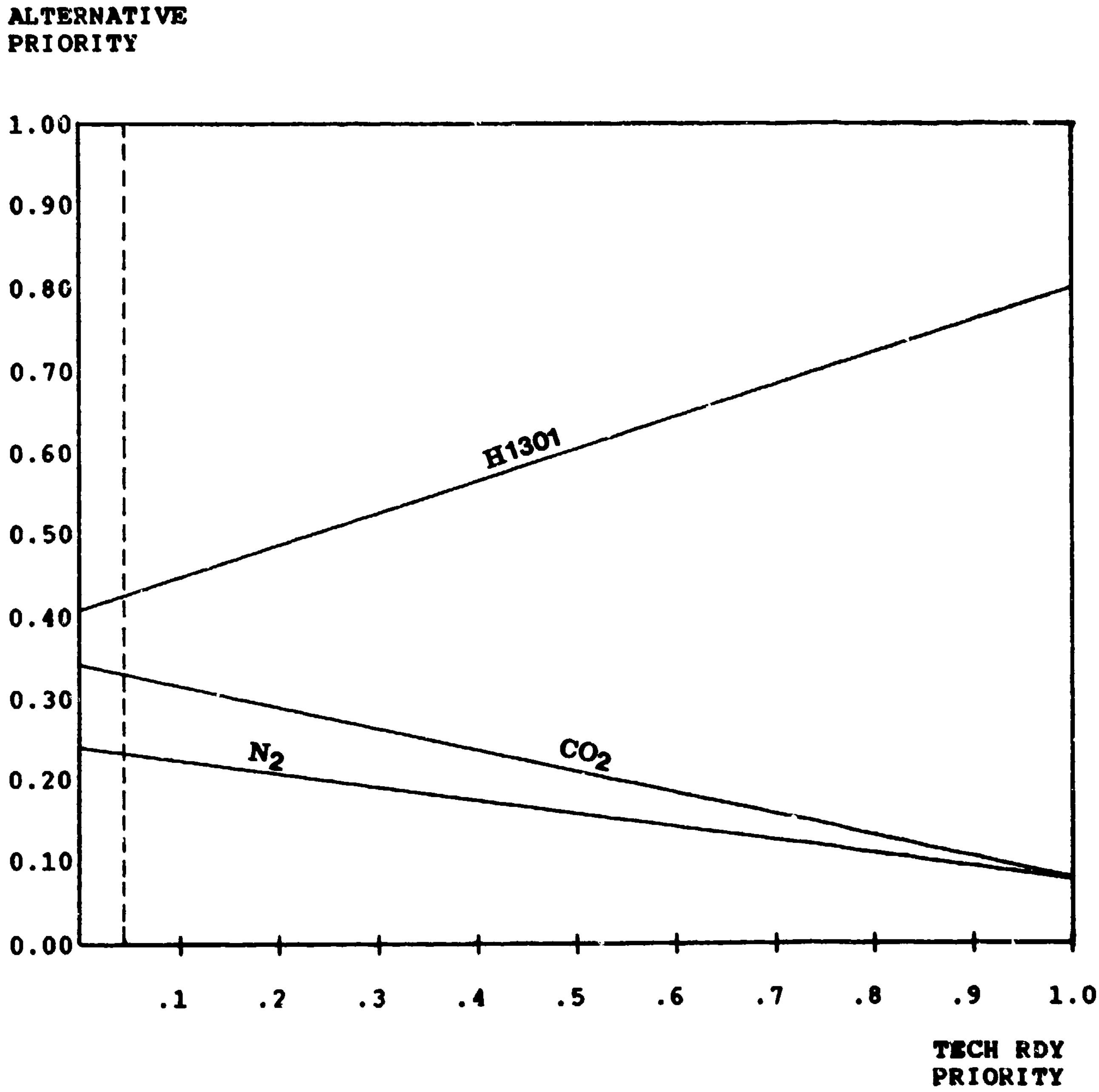

Figure B-10

Sensitivity of Alternatives' Priorities
to Priority of the Technical Readiness MOE
Large Fire/Explosion Prevention Scenario

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The potential for a fire or catastrophic explosion on board the space station is discussed in the context of the unique station environment. The need for an interim method of fire extinguishment, pending further space fire research, is identified. A systems engineering approach is used to define objectives and measures of effectiveness, identify candidate alternatives, analyze the performance of each alternative, and select the most promising alternative for each of two possible station fire scenarios. The results indicate that a portable carbon dioxide system would be preferable for use on a localized fire, while a total flooding Halon 1301 system would be the best alternative to combat a large fire or prevent a possible hydrogen explosion in a module.